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Natural Philosophy.

HYDROSTATICS

AND

PNEUMATICS

BY

THE REV. DIONYSIUS LARDNER.

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IT IS NOT EASY TO DEVISE A CURE FOR SUCH A STATE OF THINGS (THE DECLINING TASTE FOR SCIENCE); BUT THE MOST OBVIOUS REMEDY IS TO PROVIDE THE EDUCATED CLASSES WITH A SERIES OF WORKS ON POPULAR AND PRACTICAL SCIENCE, FREED FROM MATHEMATICAL SYMBOLS AND TECHNICAL TERMS, WRITTEN IN SIMPLE AND PERSPICUOUS LANGUAGE, AND ILLUSTRATED BY FACTS AND EXPERIMENTS WHICH ARE LEVEL TO THE CAPACITY OF ORDINARY MINDS.

QUARTERLY REVIEW FOR FEB. 1831.

TREATISE

ON

HYDROSTATICS AND PNEUMATICS,

by the

REVD DIONYSIUS LARDNER, LL.D. F.R.S.



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CHAP. I.

INTRODUCTION.

DIVISION OF THE PHYSICAL FORMS OF MATTER. — THE SOLID AND LIQUID STATES. — COHESION. — REPULSION. — HEAT. — SUBJECT OF HYDROSTATICS.

(1.) To investigate and explain the phenomena of nature, and to exhibit with clearness and perspicuity the laws which prevail among them, it is necessary to group the objects and appearances which are under consideration in classes distinguished by definite lines of separation. This system ought, however, to be regarded as artificial, and adopted as an aid to the limited powers of the human mind, rather than as corresponding to the actual state of the natural world. Material substances, and the various relations which are developed by their mutual agency, exist separately and individually; science arranges them in classes, according to certain similitudes and analogies which are observed among them; but this classification is often to a great extent arbitrary, and the individuals of one class are by imperceptible degrees shaded off into those of another, like the languages, manners, and habits of adjacent countries between which no natural boundary

is placed. It must be admitted that, under such circumstances, classification does a violence to nature; but yet the aids which it affords to the investigation of her laws, and the impulse which it gives to the general progress of discovery, are advantages which outweigh the objections which lie against it.

The division of bodies, or rather of the physical states in which bodies are found, into solid and fluid suggests these reflections. Two opposite influences are observed to pervade the material world. The cohesive principle is one, in virtue of which the component particles of all bodies have a tendency to collect and consolidate themselves into hard and dense masses. This principle is opposed by one of a contrary nature, which generally seems to be connected, if not identical, with that of heat. By virtue of this latter, the elementary molecules of the body which it pervades have a disposition to separate, fly asunder, or repel each other. In different bodies these two opposing forces have different relations, upon which the physical state of the body depends. If the cohesive influence predominate over the repulsive in any considerable degree, the particles of the body are held together in a solid concrete mass, not separable by any force less in amount than that by which the cohesive attraction which binds the particles together exceeds the repulsive force which tends to separate them. If, on the contrary, these two principles have an opposite relation, and the repulsive force which gives the particles a disposition to fly asunder prevail over the cohesive force, then the elementary parts of the body will separate indefinitely, and dilate and spread themselves through any vacant space to which they have free access. Such is the case with atmospheric air, and all other bodies existing under the gaseous form. Between these two opposite states there are an infinite variety of others, corresponding to all the possible relations which can subsist between the cohesive and repulsive forces. Nevertheless there is but one intermediate state which is distinctly recognised in mechanical science, to explain which it will be necessary

to take into consideration another force, viz. the gravity of the component particles. A body is said to be solid when the cohesive force by which its particles are held together is not only sufficiently powerful to neutralise the repulsive force which may tend to separate them, but also to resist the tendency which they have to fall asunder, like the grains of a mass of sand, by their own weight. If this be the case, the body, placed upon a level plane, or enclosed in a vessel sufficiently large to contain it, will maintain its figure; nor will its projecting corners or protuberant angles drop off in obedience to their gravity, but will be held firm in their relative positions. If, however, the cohesive force, though sufficient to prevent the separation of the constituent particles of a body by reason of the repulsive force which depends on the presence of heat or any other cause, yet be unable to prevent their falling asunder by their own weight, then the mass of the body, if it were placed upon a plane, would be scattered over the surface by the unresisted tendency which the particles have to fall asunder by their gravity; and if the body were placed in a vessel which by its sides would restrain the particles, they would then fall into every cavity of the vessel, and, all the lower parts being filled, the upper part of the mass would settle itself into a level surface. Such is the case of water, and all other bodies in the liquid form. There are, however, various states between this of decided liquidity, and that already described of decided solidity. The gradual transition of glue from the solid state to the soft and viscid, and finally to the perfect liquid, will elucidate these observations. The division of mechanical science, on which we are now about to enter, is confined to the consideration of bodies in a perfectly liquid state; and, as water has been assumed as the type of all other liquids, this division of the science has been called HYDROSTATICS.*

* The terms *hydrodynamics* and *hydraulics* are used to express certain divisions of the science. It will be convenient, however, in the present case, to embrace the whole under the title Hydrostatics.

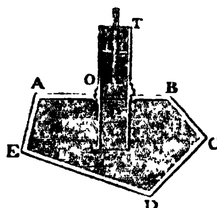
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PRESSURE OF LIQUIDS.

PRESSURE TRANSMITTED EQUALLY IN ALL DIRECTIONS. — EXPERIMENTAL PROOF OF THIS. — A LIQUID IS A MACHINE. — HYDROSTATIC PARADOX. — BRAMAH'S HYDROSTATIC PRESS. — HYDROSTATIC BELLOWS. — VARIOUS USEFUL APPLICATIONS OF THIS PROPERTY. — MEANS OF TRANSMITTING SIGNALS. — DR. ARNOTT'S SUGGESTION OF ITS APPLICATION IN SURGICAL CASES. — ILLUSTRATIONS FROM THE ANIMAL ECONOMY. — CIRCULATION OF THE BLOOD.

(2.) THE most striking quality of bodies which depends on the fluid state, and that, indeed, by which this state is mainly distinguished from the solid, is the power to transmit pressure equally in every direction. In mathematical treatises, this property is usually taken as the definition of fluidity, and as the basis of the reasoning by which the whole superstructure of the science is raised.

Fig. 1.

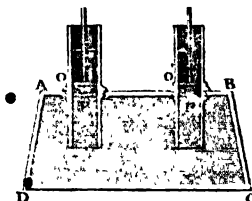


To render this property intelligible, let us suppose a close vessel of any form, such as A B C D E, *fig.* 1., having an aperture at O in which a tube or cylinder, O T, is inserted. Let us conceive this vessel completely filled with liquid to the level of the mouth, O, of the aperture. Let us now suppose a solid piston or plug, P, inserted in the tube, and pressed downwards until it comes into contact with the liquid. If the piston thus

circumstanced be urged upon the liquid with any given force, as that of one pound, an equal pressure will be transmitted to every part of the surface of the vessel equal in magnitude to the base of the piston, P. Thus, if the base of the piston be equal to one square inch, then a pressure of one pound will be excited on every square inch of the inner surface of the vessel, and a force tending to burst the vessel will be produced, the total amount of which will be as many pounds as there are square inches in the inner surface of the vessel. If the whole inner surface of the vessel amounted to 10,000 square inches, then a pressure of one pound on the piston would produce a force tending to burst the vessel, the whole amount of which would be 9999 pounds.

(3.) This property may be conceived to be experimentally established in the following manner:—

Fig. 2.



Let A B C D be a close vessel (*fig.* 2.), the top of which, A B, is horizontal. Let O, O′ be two apertures of the magnitude of a square inch, and into these let two cylinders be screwed. Let water, or any other liquid, be now poured into the vessel, until its surface reach the apertures O, O′, and every part of the vessel be filled. Let pistons be inserted in the cylinders, so as to move water tight in them, and let the piston P be loaded so as to press upon the surface of the water with a force equal to one pound. If the piston P′ press on the surface of the water with a force less than one pound, it will be observed immediately to rise, while the piston P

descends. Thus it appears that the pressure transmitted by means of the water from the base of the piston P to the base of the piston P′ is not less than a pound. Now suppose the piston P′ to press upon the surface of the water with a force greater than a pound, then the piston P′ will descend in the cylinder, and the piston P will rise. Thus it appears that the force of one pound acting at P transmits to P′ a pressure which is unable to resist a force greater than a pound. From these two experiments it appears that the pressure transmitted to P′ is neither greater nor less than a pound, and is therefore equal to a pound.

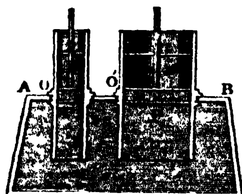
This may further be verified by loading the piston P′ so as to excite upon the liquid a pressure amounting to one pound. It will then be observed that the pistons will just balance one another. In general it will be observed, that so long as the two pistons are equally loaded, whatever be the amount of the force acting on them, they will balance each other, and neither will be displaced; but at the moment when any force is given to one greater than that which acts upon the other, however inconsiderable the excess may be, that which is urged by the greater force will descend, and will transmit a force to the other which will compel its ascent.

It therefore appears that any force whatever, which acts upon a square inch of the surface of the water at P, pressing it inwards, will produce an equal force upon the square inch of surface forming the base of the piston P′, tending to force it outwards. It is evident that this would be equally true if the surface which forms the base of the piston P′ were a part of the inner surface of the vessel, and that no aperture or cylinder existed at O′. It is also evident that the same results would be obtained, in whatever part of the vessel the aperture O might be placed; and therefore we infer that every separate square inch of surface receives from the liquid in contact with it a pressure equal in amount to the pressure which is excited on the water by the piston P.

This important property may be further elucidated as follows:—

We have supposed that the two apertures and the pistons which fill them were equal in magnitude. Let us now suppose that the aperture O′ is ten times the magnitude of the aperture O (*fig.* 3.). It follows, from

Fig. 3.



what has been already explained, that a pressure of one pound acting inwards at P will produce a pressure of one pound acting outwards on every square inch in the base of the piston P′; and therefore the piston P′ will be urged upwards by a force amounting to ten pounds. Accordingly, we shall find that if this piston be loaded with a weight of ten pounds, it will resist the pressure of the liquid, and will not suffer itself to be forced upwards in the cylinder; but, on the other hand, this weight will not enable it to force the liquid inwards, and it will merely maintain its position. If it be loaded with a weight greater than ten pounds, it will force the liquid inwards, and will raise the piston P; and if it be loaded with a weight less than ten pounds, the piston P will force it upwards. It appears, therefore, that the pressure excited on the ten square inches of surface forming the base of the piston P′ is ten pounds, and neither more nor less. In the same manner, whatever be the proportion which the base of the greater piston P′ bears to the base of the lesser piston P, in exactly the same degree

will the force transmitted by the liquid from P to P′ be multiplied.

There are some circumstances which impair the accuracy with which the practical results of the experimental illustrations, conducted in the manner just described, represent the conclusions at which, by reasoning, we have arrived. That the pistons P, P′ may move in the cylinders so as not to allow the liquid to escape between them and the inner surface of the tube, it is necessary that they should press upon that surface with a certain force: this pressure will unavoidably be accompanied by friction; and, before the pressure excited on one piston can produce a perceptible effect in moving the other, an excess of force must be produced sufficient to overcome the friction of both pistons. Thus, in *fig.* 2., if the pistons be equally loaded, a small additional weight on either will not always cause the other to ascend; it will only do so when its force exceeds the amount of the resistance occasioned by the friction of the pistons.

This inconvenience may be removed by applying the pressure on the surface of the liquid at O and O′ by some means which will not be attended with perceptible friction. Such means are easily found; and although they may at the first view appear to confirm the theory by a more indirect process, yet, when duly considered, it will be perceived that the method is not only direct, but more satisfactory than the former.

Fig. 4.

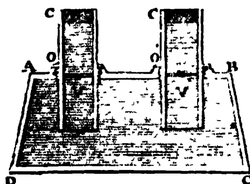
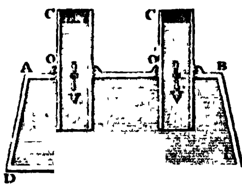


Fig. 5.



(4.) Let us suppose the pistons P, P′ removed from the cylinders, and let circular plates, so formed that they

shall exactly cover the apertures O, O′, turn upon rods which extend across the holes, so that, being turned upon these rods, they will in one position completely stop the apertures, their flat faces being presented to the liquid, as in *fig.* 4.; while in another position they will leave the apertures open, having their edges turned towards the liquid, as in *fig.* 5. Thus, in the position represented in *fig.* 4., all communication between the liquid in the vessel and the external part of the cylinder is cut off, while in the position represented in *fig.* 5. there is a free communication.

First, let the two valves V, V′ be closed, as in *fig.* 4., and let one pound of oil be poured into the cylinder C. It is evident that the valve V will now sustain a pressure of one pound; and if that valve were removed, as the oil would not mix with the water but rest upon it, the water would sustain the same pressure. Let the valve V be turned till it assumes the position represented in *fig.* 5.: the weight of the oil will now press upon the surface of the water; and, as there will be no sensible friction between the oil, and the surface of the cylinder, an undiminished pressure of one pound will be transmitted to every square inch of the surface of the vessel, and, among others, to the surface of the valve V′, which will be pressed upwards with a force of that amount. That the valve V′ is pressed by such a force may be made manifest as follows: — Let a pound of oil be poured into the tube C′: this will press upon the valve V′ with a force of one pound; and if the valve V′ be turned into the position represented in *fig.* 5., the same pressure will act upon the surface of the water below. It will then be observed that this surface will maintain its position, neither forcing the oil up, nor being forced down by it. If less than a pound of oil had been poured into the tube C′, the pressure of the water below would prevail, and its surface would rise in the tube; and it would only be restored to its former position by pouring in so much more oil as would make the weight of the whole one pound. If still more were poured in, the pressure of

the oil would prevail, and the surface of the water would sink in the tube. Thus it appears conclusively, that a pressure of one pound excited at V is transmitted un-

Fig. 4.

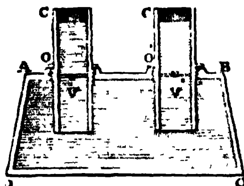
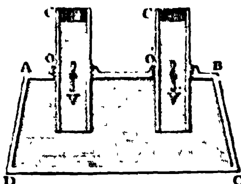


Fig. 5.



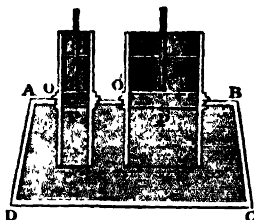
diminished to V′; and in the same way is transmitted every square inch on the surface of the vessel.

(5.) By the same reasoning it may be shown, that if the cylinder C′ were greater than C, it would require a proportionally greater weight of oil to resist the ascent of the water, and we should arrive at the same conclusions as we have obtained respecting the piston represented in *fig.* 3.

(6.) By this singular power of transmitting pressure, a fluid becomes, in the strictest sense of the term, a *machine*, and one of unequalled simplicity and almost unlimited power: as such it is amenable to all the laws, and fulfils all the conditions, to which ordinary machines are subject. The surprising effects which are consequent on the property of liquids which we have just explained, exhibited under various forms, which we shall presently have occasion to notice more particularly, have acquired for it the name of the "hydrostatic paradox." But, in truth, there is nothing in these effects more deserving the title of paradox than those which attend every machine. In various parts of our treatise on Mechanics, and more especially in the twelfth chapter of that volume, it has been proved that there is nothing paradoxical, or repugnant to the results of common observation, in the effects produced by machinery. We shall now endeavour to show that the same principles are

applicable, and the same explanations satisfactory, when a liquid is used as a machine; that is, as a means of transmitting force from one point to another.

Fig. 6.



A force of a pound acting on the piston P, *fig.* 6., holds in equilibrium a force of ten pounds acting on the piston P′. In this case, however, it must not be supposed that the piston P supports the ten pounds which press down the piston P′: the bottom of the vessel sustains by its resistance nine of the ten pounds acting on the piston P′, and the remaining pound alone is resisted by the piston P.

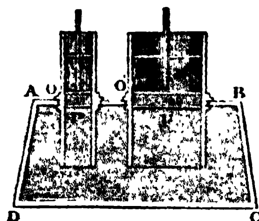
The circumstances attending the action of these forces differ in nothing from those of a lever of the first kind, supporting a weight of ten pounds on the shorter arm, balanced by a weight of one pound on the longer arm. The liquid performs the office of the bar, by transmitting the effect of the lesser weight to the greater; and the surfaces of the vessel which contains the liquid perform the office of the fulcrum by sustaining both the power and weight.*

If the piston P be used to raise the piston P′, instead of merely supporting it, what has been regarded as paradoxical in the process may likewise be explained almost in the same words which have been used in explaining several machines in our treatise on Mechanics. If the

* Mechanics, p. 171. (241.)

piston P be made to descend one inch, a quantity of water which occupies one inch of the cylinder C will be expelled from it; and as the vessel A B C D is filled in

Fig. 6.



every part, and its sides cannot yield, the piston P′ must be forced up until room be obtained for the water which has been expelled from C. But as the cylinder C′ is ten times larger than the cylinder C, the height through which the piston P′ must be moved to obtain this room will be ten times less than that through which the piston P was caused to descend. Thus, while one pound on the piston P was moved through one inch, a weight of ten pounds on the piston P′ has been moved through the tenth of an inch. By repeating this process ten times, we shall move ten pounds on the piston P′ through a height of one inch, by ten distinct efforts, each of which moves one pound through one inch. The force expended, and the effect produced, is therefore the same as if the weight of ten pounds, with which the piston P′ was loaded, were divided into ten equal parts, and these parts severally raised by ten distinct efforts through the height of an inch. The force, therefore, expended to produce a given effect is the same as if no machine was used.*

(7.) It is not the least surprising circumstance in the

* See Mechanics, p. 161. (226.)

history of physical science, that this property of liquids, though long known, and, indeed, the subject of curious observation, should have continued, until a comparatively recent period, a barren fact. The engine known by the name of the HYDROSTATIC OR HYDRAULIC PRESS, and sometimes, from the name of the engineer who gave it its present form and brought it into general use, BRAMAH'S PRESS, is nothing more than a simple and direct practical application of the property which we have just investigated.

A small cylinder, C, *fig.* 7., is furnished with a piston or plug, A, which moves water tight in it; at the bottom of this cylinder there is a valve, B, which opens upwards and communicates with a tube below, which descends into a vessel or reservoir of water. In the side of the cylinder C there is a narrow tube, D, inserted in the cylinder, and communicating at E with another cylinder, C′, of much greater dimensions. In this cylinder there is a large piston, A′, the rod of which is directed against whatever object the machine is intended to sustain or move. We shall at present suppose it applied to an ordinary press: G H I K represents a strong iron frame, and F a square plate moveable in it and resting on the piston rod. As the piston rod is moved up, the plate F is forced up towards the top of the press H I, so that any substance placed between the plate F and the top H I is submitted to pressure. In the tube D E there is a valve, O, which opens towards the great cylinder C′; and in the same tube there is a stop-cock, P, by which a communication with the cistern below may be opened and closed at pleasure.

The rod of the small piston A is connected at X with a lever, L M, which plays upon a fulcrum at M. The press is worked by raising and depressing alternately the lever at L, and the process is effected as we shall now describe.

Suppose the water, if there be any in the cylinder C′, is discharged into the reservoir by the cock P, which is

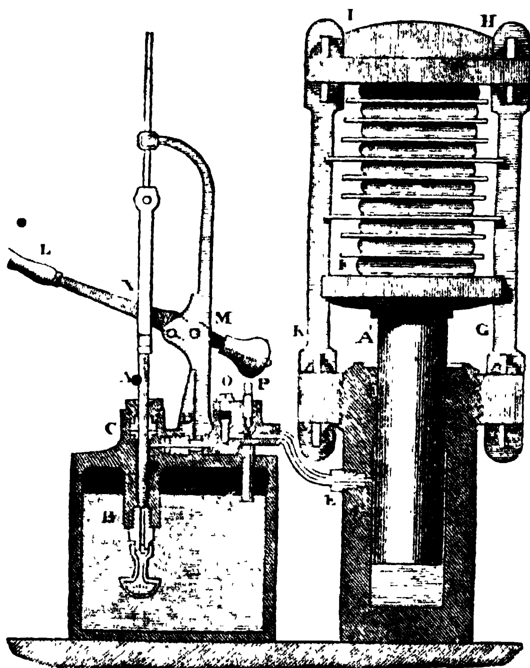
then closed; the piston A′ will then fall to the bottom of the cylinder. Let us also suppose that the piston A is at the bottom of the cylinder C. If the lever L be now raised, the piston A will be elevated, and the space below it in the cylinder, being free from air, the atmospheric pressure * will force the water in the reservoir up through the valve B so as to fill the cylinder C: this water cannot return through the valve B, since that valve opens upwards, and the weight of the water above it only keeps it more firmly closed. Let the lever L be now depressed: the water below the piston A will be forced through the valve O, and through the tube DE, into the great cylinder C′. Let this process be continued until the space in the great cylinder below the piston is completely filled with water: when that is accomplished, the pressure of the piston A will be transmitted to the piston A′, multiplied in the proportion of the magnitude of the piston A′ to that of the piston A (3.). Thus, if the magnitude of the piston A′ be a thousand times that of A, a pressure of ten pounds on the piston A will produce a pressure of ten thousand pounds on the piston A′. During the operation of the machine, at the intervals of the ascent of the piston A, its action on piston A′ is suspended; and if the tube of communication DE were open, the piston A′ would press upon the valve B during every ascent of the piston A, and would resist the entrance of water into the small cylinder, and thus the operation of the machine would be obstructed: but the valve O opening towards the great cylinder C′ prevents this, and performs, in some degree, the office of a ratchet wheel.† The water having once passed this valve cannot return; and while the piston A is being raised, this valve sustains the pressure transmitted by the great piston A′. Thus, the great piston, being once raised through any space, cannot recoil.

When it is required to release the substance which is submitted to the action of the press, it is only necessary

* This effect will be explained in Pneumatics.

† See Mechanics, p. 179. (253.)

Fig. 7.



to open the screw valve-cock P. The water will be forced by the weight of the great piston A′ through the tube E, and, passing through the tube of communication to which it is admitted by the open stop-cock P, it will be discharged into the cistern from which it was originally raised by the pump A B.

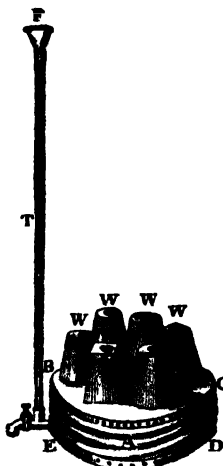
The mechanical efficacy of the lever L M adds to the power of this machine. We have seen that a force of ten pounds acting on the small piston will produce a force of 10,000 pounds on the great one; but if the greater arm L M of the lever be ten times the length of the shorter arm M X, then a force of one pound at L will produce a pressure of ten pounds at X *, and therefore also at the base of the piston. Under these circumstances, therefore, it appears, that a moving power of one pound will produce at the working point an effect equal to 10,000 pounds. With such a machine the hand of a child, applied at L, would break a bar capable of sustaining many tons.

It is evident that the power of this machine depends partly on the proportion of the magnitudes of the two pistons, and partly on the leverage of the arm L M. By varying these proportions in the construction of the press, it may be adapted to any required purpose, and may receive any degree of power. The arrangement of the parts may also be varied, but the principle of action is always the same.

The great advantage which this press possesses over those which are worked by a screw is obvious. Between solids and fluids there is little or no friction; and, accordingly, in the hydrostatic press no force is lost by friction, except what is necessary to overcome the friction of the pistons in the cylinders. On the contrary, of all machines the screw is that whose action is most impeded by friction, and in every screw-press the moving power is robbed of a large portion of its efficacy by this cause.

* See Mechanics, p. 167. (235.)

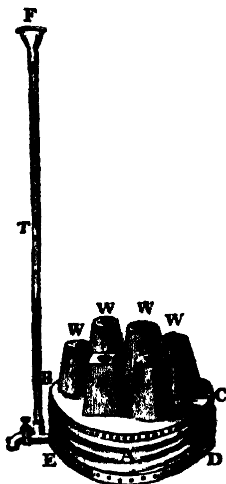
Fig. 7.



(8.) The apparatus commonly called the *hydrostatic bellows* is another form under which the hydrostatic paradox is frequently presented. Two flat boards, B C and D E, *fig.* 7., are united by leather or flexible cloth A. A short tube communicates with the interior of the bellows, and terminates in a stop-cock, by which the liquid with which the bellows are occasionally filled may be discharged. From this short tube a long tube T rises perpendicularly, and terminates in a funnel F. The upper board B C is loaded with weights W, which press it against the lower board D E; the cloth which unites them being collected in folds between them. If water be now poured into the funnel F, it will descend through the tube, and enter between the boards. By continuing to supply water to the funnel, a column will be maintained in the tube, which by its weight will press upon the water contained between the boards, and will thereby sustain the weights W. As the supply is con-

tinued, these weights will be gradually raised as far as the magnitude of the leather which unites the boards will permit.

Fig. 7.



In this case the weight of the column of water in the tube T performs the part of the smaller piston in the hydrostatic press, while the upper board, loaded with the weights, sustains the effect on the greater piston. If the section of the tube T have the magnitude of one square inch, and the upper board B C have a surface of 1000 square inches, then a column of water in T weighing one pound will sustain a weight on the board amounting to 1000 pounds. This may be explained in the same manner, and nearly in the same words, as were used respecting the action of the hydrostatic press. If the funnel be removed and six men stand on the board B C, one of them, blowing into the tube T with his mouth, may produce a sufficient pressure on the column of water, to raise the board and its load.

Fig. 8.



(9.) If a long narrow tube A, *fig.* 8., be inserted perpendicularly into a vessel B, filled with water, the weight of a few ounces of water may be so applied as to burst the vessel, whatever be its strength, provided the tube be sufficiently long and narrow. This will be easily understood upon the principles already explained. Let us suppose that the magnitude of the bore of the tube is the hundredth part of a square inch, and that it ascends perpendicularly to such a height above the vessel that it may contain an ounce of water, that part of the water in the vessel which is immediately under the mouth of the tube will receive a pressure of one ounce from the incumbent column. The magnitude of the mouth of the tube being the hundredth of a square inch, it follows, from what has been already proved, that every hundredth part of a square inch in the surface of the vessel will sustain a pressure of one ounce, and therefore every square inch will sustain a pressure of 100 ounces. A square foot contains 144 square inches, and therefore every square foot will sustain a pressure of 14,400 ounces, or 900 pounds. Hence if the base of the vessel measure nine square feet, and its sides thirty-six square feet, and its top nine square feet, we shall have a total surface of 54 square feet, each square foot bearing a pressure of 900 pounds, and the whole surface sustaining a pressure, tending to burst the vessel, amounting to more than twenty-one tons, and this enormous force is produced by the mechanical modification which the weight of one ounce of water undergoes.

(10.) The property of liquids, which has been under consideration, points them out as an easy, simple, and effectual means of transmitting force to any distance, and under circumstances in which other mechanical contrivances would be totally inapplicable. It is only necessary to carry a tube filled with a liquid from the point where the force originates, to the point to which it is to be transmitted; and as the shape or position of

the connecting tube or pipe does not affect the property of the fluid which it contains, there is scarcely any conceivable impediment which can prevent the transmission of the force from the one point to the other. A pressure excited on the liquid at one end of the tube, will be communicated to any surface in contact with the liquid at the other end, whether the tube between the two extremities be straight, curved, or angular, or whether it pass upwards, downwards, or in an oblique or horizontal direction. It may be carried through the walls of a building, through the course of a river, under, over, or around any obstruction or impediment, or, in fact, according to any course or direction whatsoever. If a tube filled with water extended from London to York, a pressure excited on the liquid at the extremity in London, would be instantaneously transmitted to the extremity at York. It has been suggested, that such means might be used for telegraphic communications in situations where the frequency or importance would justify the expense of laying down pipes or tubes. An ingenious person in this country has tried the experiment with this view, and has laid down several miles of pipe for the purpose. Such a method of communication would have the advantage of being independent of those accidental interruptions to which lights, signals, and other similar contrivances are exposed.

(11.) The power of liquids to transmit pressure has been proposed to be applied to surgical purposes by Dr. Arnott. It would indeed seem to be peculiarly applicable in cases where it is necessary to produce a pressure on some internal part, which cannot be approached except by a tube or channel, through which an instrument cannot be safely or conveniently inserted. Dr. Arnott considers that a liquid might be conveyed through a flexible tube, so shaped, that when filled by the liquid the proper degree of pressure will be excited on those parts which require it. An account of these instruments may be seen in Dr. Arnott's work on Physics.

(12.) The animal economy presents innumerable

examples of the power of fluids in transmitting pressure. The bones and harder parts of the body furnish a beautiful example of a structure, in which every leading principle of mechanics, commonly so called, is illustrated. The fluids, in like manner, exhibit equally apt illustrations of the principles of hydrostatics. The heart, the fountain from which the blood is supplied to all parts of the system, is an instrument possessing great power of expansion and contraction: by exciting a pressure upon the blood, it impels that fluid into the arteries, pressing forward what has already filled them through proper channels of communication into the veins. These various pipes and conduits are formed of an elastic material, capable of continuing the pressure commenced at the heart, and thus urging forward the stream of liquid, until its circulation is completed.

As in the pipe DE, *fig.* 6, of the hydrostatic press, valves are provided in proper places in the various tubes through which the circulation is carried on. These valves are so contrived, that the blood is admitted to pass freely in obedience to the impulse it receives from the muscular pressure; but when that pressure is intermitted the fluid cannot return, and the resistance of the closed valve supplies the place of the moving power whose action is suspended.

The muscular power of the heart to excite a pressure on the blood is placed in a very striking point of view, by an experiment recorded in a work by Dr. Hales, called Statical Essays. A perpendicular tube is made to communicate with the blood of one of the arteries of an animal. The blood being no longer confined, rushes into the tube and ascends to a height above the level of the heart, which is proportionate to the pressure which it receives. This height necessarily varies in different animals; in the larger and more powerful species, it is much greater than in the smaller ones. In the case of a horse, the column will ascend to about ten feet above the heart. The pressure to which it is subject in the veins is much less than in the arteries. Dr. Hales found

that in the human body, the pressure of the arterial blood was capable of sustaining a column eight feet in height, and amounted to four pounds on the square inch; while the pressure of the venous blood did not exceed a quarter of a pound on the inch, and only sustained a column six inches in height.

CHAP. III.

OF THE PRESSURE PRODUCED BY THE WEIGHT OF A LIQUID.

PRESSURE PROPORTIONAL TO THE DEPTH. — PRESSURE ON THE HORIZONTAL BOTTOM AND PERPENDICULAR SIDES OF A VESSEL. — EXPERIMENTAL PROOFS OF THE PROPERTY. — TOTAL PRESSURE ON THE PERPENDICULAR SIDE OF A VESSEL COMPUTED. — EMBANKMENTS, DAMS, AND FLOODGATES. — METHOD OF COMPUTING THE TOTAL PRESSURE ON THE SURFACE OF A VESSEL OF ANY SHAPE. — EXAMPLES. — GLOBE. — CUBE. — VARIOUS EFFECTS PRODUCED BY THE PRESSURE OF LIQUIDS AT GREAT DEPTHS. — — CORK FORCED INTO A BOTTLE. — WATER FORCED INTO THE PORES OF WOOD. — LIQUIDS NOT ABSOLUTELY INCOMPRESSIBLE. — EXPERIMENT TO PROVE THIS.

(13.) In the investigation contained in the last Chapter, the effects of the weight of the liquid itself were left out of consideration, and it was merely regarded as a machine by which other forces might be transmitted and modified. In the same manner, however, and upon the same principles, as it transmits and modifies other forces, it conveys the effect of its own weight through the dimensions which it occupies in the vessel which contains it. This weight excites a certain pressure on every part of the surface of the containing vessel with which it is in contact. The total amount of this pressure, as well as the portion of it which each part of the surface sustains, is to be inferred from a consideration of the weight of the liquid, its power of transmitting pressure, and the peculiar figure or shape of the vessel. It may, however, here be observed, generally, that the effect is totally different from that which would be produced by a solid.

(14.) There is one general principle by which the pressure of a liquid on the surface of the vessel which contains it may always be ascertained. Each part o.

the surface of the vessel, in contact with the liquid, sustains a pressure equal to the weight of a column of the liquid, whose height is equivalent to the depth of the part of the surface of the vessel in question below the surface of the liquid contained in the vessel. The truth of this general principle will be apparent, by considering it, first, in the more simple and obvious cases, and tracing it thence to the more complex and difficult ones.

Fig. 9.

Let ABC, *fig.* 9. be a long square pipe in a perpendicular position, each of whose sides is an inch broad. The base BC, therefore, is a square, each of whose sides is an inch. Suppose this base to be closed by a flat bottom, and let water be poured into the pipe until it attain an elevation B′C′ one inch above the bottom of the pipe. The liquid will now be in contact with a square inch of surface on each of the four sides, besides the square inch of surface which forms the bottom. Let a flat plate, cut into the shape of a square inch so as to fit the tube, be now conceived to be introduced into it, and placed immediately on the surface of the water, and in contact with it. If any weight, as 10 pounds, be placed upon this plate, the liquid below will transmit a pressure of ten pounds to every square inch of the pipe with which the water is in contact, and therefore the bottom, and each of the four sides, will severally sustain a pressure of ten pounds. This is obvious from what has been so fully explained in the last Chapter.

If the plate and the weight with which it is supposed to be pressed be removed, and ten pounds of water be poured into the pipe, the water below the level B′C′ will suffer exactly the same mechanical pressure as was before exerted by the plate loaded with the weight, and this pressure will be transmitted in the same way to the surface of the tube, by the water below B′C′. It thus appears that a perpendicular column of water, weighing ten pounds, standing above the level B′C′, will press,

not only on the bottom of the vessel, but on the sides immediately below B′C′ with a force amounting to ten pounds.

What has been proved of the column of fluid, above the level B′C′, will be equally true of any other part of the column of fluid contained in the tube. Thus the column of fluid above the level B″C″ will communicate a pressure to every square inch of the surface of the vessel below that level, amounting to its own weight.

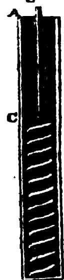
To render the explanation more clear and simple, the section of the pipe has been here supposed to be square, and its magnitude to be one inch; but a little attention and consideration will show, that the same reasoning, with slight changes, will be applicable, whatever be the magnitude of the vessel, and whatever be the shape of its base. If any part of the column is supposed to be removed, and a flat plate fitting the vessel, and loaded with a weight equal to that of the water removed be introduced, the force of this weight will be transmitted by the water below, with undiminished energy to every part of the surface of the vessel with which it is in contact. Each portion of the surface of the vessel, which is equal in magnitude to the surface of the plate, will sustain a pressure equal to the force with which the plate presses on the water. When the plate is removed and replaced by an equivalent weight of water, the same effect will be continued.

(15.) It therefore appears generally, that in every vessel whose sides are perpendicular, and whose bottom is horizontal, whatever be its shape in other respects, the pressure on the bottom will be equal to the whole weight of the fluid which it contains, while the pressure on each square inch of the perpendicular sides, will be equal to the weight of a column of the liquid, whose base is a square inch, and whose height is equal to the depth of the part of the surface of the vessel in question below the upper surface of the liquid in the vessel.

(16.) It appears from what has been stated, that not only the surface of the vessel which contains a liquid,

but likewise every part of the liquid itself, sustains a pressure from the weight of the liquid above it, and this pressure is regulated by the same law. If any portion of the liquid be selected at any given depth below the surface, that portion is pressed equally in every possible direction by the surrounding fluid, and the amount of the pressure which it thus sustains is the weight of the column of fluid perpendicularly above it. This may be easily deduced from considering the property of liquids explained in the last Chapter. It is evident that a part of the fluid, taken any where within its dimensions, sustains a downward pressure from the weight of the incumbent column; but it transmits this pressure, by the property just alluded to, in every direction around it; downwards, laterally, obliquely, &c. Now it is clear that it must encounter an equal pressure in all these directions; for if it did not, it would move away in that direction in which its force was unresisted; but as no such motion takes place, and as the particles of the fluid remain at rest, it follows that they are maintained in these places, by forces pressing them equally on every side and from every possible direction, each of which is equal to the weight of the perpendicular column of fluid above the particle so pressed.

Fig. 10.



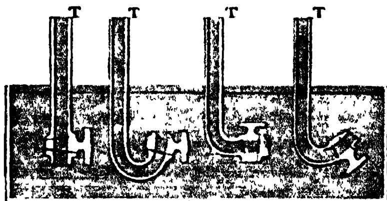
(17.) This property may easily be reduced to experimental proof. Let A B, *fig.* 10, be a strong metal cylinder, having a metal bottom at B but open at A: in this let a spiral spring be inserted, bearing a circular plate C, which moves water-tight within the cylinder, so that a force applied to the plate C will overcome the elasticity of the spring, and cause the plate to move into the cylinder towards B. The farther the plate advances within the cylinder, the more powerful, the elastic force of the spring will become, and the greater will be the force necessary to prevent its recoil. The amount of force necessary to press the plate to any proposed depth in the cylinder, may be determined by experiment, and it

is not difficult to provide a means of registering the depth within the cylinder, to which the plate may have been forced on any occasion, when the presence of an observer is rendered impossible. If such an instrument be plunged in a liquid to any depth, the pressure exerted by the fluid will force in the moveable plate; and upon observing the instrument when drawn out, the amount of the pressure will be known from the space through which the plate was forced into the cylinder. If the instrument be successively immersed to depths of 1, 2, and 3 yards, it will be found that the pressures which have acted on the spring, are in the proportions of the numbers 1, 2, 3, and are equal to the weights of columns of the liquid whose heights are respectively equal to the depths of immersion, and whose bases are equal to the moveable plate. The fact that the pressure is proportional to the depth, and equal to the weight of the incumbent column, is thus conclusively established.

That this pressure is exerted equally in every possible direction, may be shown by giving the instrument, at the same depth successively, different positions. If it be first immersed with the end A presented upwards, and the distance observed through which the plate is forced in, and then successively immersed to the same depth with the end A presented downwards, sideways, and in any other direction, it will always be observed that the distance through which the plate is forced by the pressure of the liquid will be the same, indicating thereby, that the pressures in all those directions are equal.

(18.) This important law may be established experimentally by a more easy and scarcely less direct method. Let four glass tubes T, *fig.* 11., be provided, open at both ends, and let one end of the first be straight; of the second, turned upwards; of the third, turned sideways; and of the fourth, turned in an oblique direction. At these ends let stop-cocks be placed, which may be opened and closed at pleasure. These cocks being closed, let all the tubes be immersed to the same depth in a vessel of

Fig. 11.



water. The water will then press against each of the cocks with a certain force, the amount of which it is required to ascertain. We shall suppose the bores of the tubes to be equal, although that circumstance, as will hereafter appear, cannot affect the result of the experiment. Let us suppose the diameter of the bores of each of the tubes to be half an inch.

The water, at the depth to which the tubes are immersed, is in this case acting against a circular surface, of the diameter of half an inch at each stop-cock. If the several stop-cocks be now opened, the pressure will cause the water to rush into the tubes, in the first upwards, in the second downwards, in the third sideways, and in the fourth obliquely. It will continue to flow into each until the weight of the column, which has risen in the tube, is sufficiently great to resist the pressure at its extremity. When that takes place, and not until then, the water will cease to flow into the tube. It will be observed, that in each tube the water will rise until it has attained the level of the water in the vessel, and it will then cease to flow. It follows, therefore, that the pressure of the fluid at the extremity of the tubes is equal to the weight of a column of the fluid, which extends perpendicularly from their extremities to the surface; and since the water will always rise to the level of the fluid in the vessel, whatever direction may be given to the lower extremity by bending the tube near that point, it follows, that at the same depth the pressure in every possible direction is the same.

In this mode of illustration it will easily be perceived,

that the column of water which is sustained in the tube performs the part of the stop-cock, with respect to the water which presses in at the orifice below, and that the weight of this column exactly balances this pressure.

There will be no difficulty in seeing how this experiment may be generalised. The tubes may be of any magnitudes, whether equal or unequal, and still the water will rise in them to the level of the water in the vessel; and the same will happen whatever be the liquid used. The pressure exerted at any depth below the surface is always equal to the weight of a column of the liquid whose height is equal to the depth, and whose base is equal to the surface, over which the pressure is extended. The quantity of liquid whose weight expresses this pressure, may always be determined arithmetically, by multiplying the number of inches in depth below the surface of the liquid, by the number of square inches in the surface on which the pressure is exerted. The product of these numbers will be the number of solid inches of the liquid, whose weight is equal to the pressure. It must, however, be understood, that in this mode of calculation, the surface pressed is supposed to be horizontal, or if it be oblique, its dimensions must be very small, compared with the depth.

The following experiment furnishes another illustration of the property by which the pressure of a liquid increases with the depth:—Let a bladder be attached to the extremity of a glass tube, and let it be filled with mercury to a small height above the point where it is attached. Let equal small divisions be marked upon the tube, beginning from the surface of the mercury. If the bladder thus filled be immersed in a vessel of water, the pressure of the surrounding liquid will cause the mercury to ascend in the tube. Let it be immersed to such a depth that the mercury will rise through one division of the tube, and let the depth of immersion be observed; let the tube be then immersed to twice that depth, and the mercury will be observed to rise through another division. Being immersed to three times the

depth, it will rise to a third division, and so on. It therefore appears that the pressure upon the bladder increases in proportion to the depth.

(19.) Concluding, then, that every part of a liquid suffers and transmits a pressure, arising from the weight of the incumbent liquid, that this pressure is always proportional to the depth, and is equally exerted in every direction, we may easily obtain theorems respecting the pressure sustained by the surface of vessels which contain liquids of a much more general nature than those which have led to the preceding investigation.

Whatever be the shape of the vessel which contains a liquid, each square inch of its surface suffers a pressure equal to the weight of a column of the liquid, whose base is a square inch, and whose height is the depth of that part of the surface of the vessel below the surface of the liquid. This follows immediately from the principle which has just been established; for the liquid which is in immediate contact with any part of the surface of the vessel, sustains a pressure in a direction perpendicular to that surface, to the amount just mentioned; and it is evident that the surface must balance and resist that pressure.

By the aid of the peculiar language and symbols of mathematical science, general rules or formularies may be given, by which the whole pressure of a liquid on the surface of a vessel of any proposed figure may be computed. Although great practical facility, not only in calculation but also in reasoning, may be derived from the use of such formulæ, yet they must be understood to express nothing more than what has been already explained. The method by which they express it is, however, attended with great convenience, and affords considerable advantages in the application of the general principle to particular cases.

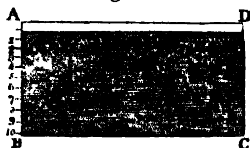
(20.) An obvious consequence of the property now explained is, that the pressure produced upon the surfaces of the vessel containing a liquid, can never in any case be less than the weight of the liquid, but will not

unfrequently amount to many times that weight. Since the general methods of determining the pressure on surfaces do not admit of familiar explanation, we shall endeavour to explain the principle by its application to such particular cases as can be rendered intelligible, without mathematical symbols.

(21.) If the surface which sustains the pressure be horizontal, every part of it being at the same depth will suffer the same pressure. In this case, therefore, it is evident that the total pressure which the surface sustains is the weight of all the liquid which is perpendicularly over it, or what is the same, the weight of a column of the liquid, whose base is equal to the surface, and whose height is equal to the depth.

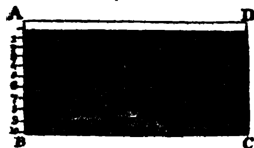
(22.) If the surface which suffers the pressure be not horizontal, its several parts will be at different depths, and therefore will suffer different pressures. If a point could be found whose depth is an average of all the different depths, then the total pressure would be the same as if the whole surface were uniformly subject to the pressure sustained by this point, and the total amount of the pressure would be equal to the weight of a column of the liquid, whose base is equal to the surface pressed, and whose height is equal to the depth of that point. This will perhaps be more clearly comprehended by particular examples.

Fig. 12.



Let A B C D, *fig.* 12., be a vessel with a flat square bottom and perpendicular sides; and suppose it filled with water; and let the side A B be supposed to be divided into ten equal parts, marked by the numbers 1, 2, 3, 4, to 10: the pressure at the point 1 we shall suppose to be one pound. The point 2 being at twice

Fig. 12.



that depth, will sustain a pressure of two pounds. The point 3 will sustain a pressure of three pounds, and so on, the lowest point sustaining a pressure of ten pounds. Since, therefore, the intensity of the pressure from A to B increases uniformly, the point which sustains the average pressure will be found at the middle of the depth A B. This point is that which is marked 5. If we suppose the whole surface A B to sustain the same pressure as that which the point 5 suffers, the total pressure will be the same as at present. A very slight consideration of the effects will make this evident. At present the point 6 sustains a pressure of six pounds, and the point 4 sustains a pressure of four pounds, making a total of ten pounds. If these two points each sustained a pressure of five pounds, which is the average pressure, the total pressure would still be the same, ten pounds. In like manner, the point 7 at present sustains a pressure of seven pounds, and the point 3 a pressure of three pounds, which together make ten pounds. If each of these points sustained a pressure of five pounds, the sum would be the same. It is evident that the same reasoning will apply to all points equally distant above and below the middle point 5. The pressure on each point below it exceeds the pressure at 5 by exactly as much as the pressure on a point equally distant above it falls short of the pressure at 5. Thus the excess and defect mutually compensate each other, and a general average is obtained.

From what has been now stated, it appears that the total pressure on the perpendicular side of a vessel filled with a liquid, is the same as if that side were converted

into an horizontal bottom, and half the depth of liquid rested on it.

It also appears that the pressure on the perpendicular side is entirely independent of the quantity of liquid which the vessel contains. The perpendicular sides of a trough, when filled with a liquid, will sustain the same pressure whether the trough be wide or narrow. If the sides be separated by an interval of only a quarter of an inch, and the trough contains only a quart of water, the pressure on the sides will be the same as if the sides were separated many yards, and the trough contained several barrels of water.

(23.) If the sides of the vessel be perpendicular, and the bottom be horizontal and flat, the pressure on the sides may be estimated in the same manner as above, whatever be the shape of the bottom. The point of average pressure is in this case always at half the entire depth below the surface of the liquid; and the total pressure is the same as if this average pressure were uniformly diffused over the entire surface of the sides in contact with the liquid. Thus, if the vessel be cylindrical, and the circumference of its base be ten feet, the depth of the fluid in the vessel being eight feet, the total surface of the sides in contact with the fluid is eighty square feet. The medium pressure is that which is sustained by a point at the depth of four feet, and therefore is equal to the weight of four feet of the liquid. Of the eighty square feet, forty are subject to a less pressure than this medium, and the other forty are subject to a greater pressure: these two effects compensating each other, the total pressure is the same as if the medium pressure were diffused over the whole eighty feet. The whole lateral pressure is, therefore, the same as would be produced upon the bottom of a vessel of eighty square feet in magnitude, with perpendicular sides, and containing the liquid to the depth of four feet. This pressure would, in fact, be the whole weight of the fluid in the vessel, the quantity of which would be

found in solid feet by multiplying the bottom by the depth; that is, eighty by four; that is, 320 solid feet.

(24.) The rule deduced from this example, for calculating the lateral pressure, is generally applicable to all cases where the vessel containing the liquid has a flat horizontal bottom and perpendicular sides. Find the number of square feet in the sides below the surface of the liquid contained in the vessel; multiply that by the number of feet in half the depth of the liquid: the product will express the number of solid feet of the liquid, the weight of which is equal to the lateral pressure. The number of square feet in the sides may always be found, by multiplying the number of feet in the circumference of the bottom by the number of feet in the depth of the liquid.

From this rule some curious consequences follow. The pressure against the sides produced by the liquid may exceed in any proportion, however great, the whole weight of the fluid which causes this pressure. If the lateral surface in contact with the fluid be double the magnitude of the bottom of the vessel, then the lateral pressure will be equal to the pressure on the bottom and therefore equal to the whole weight of the fluid for, in this case, the lateral pressure will be equal to the weight of the fluid which would fill a vessel with perpendicular sides, having a bottom of double the size, but filled only to half the depth. The quantity of liquid whose weight expresses the pressure would, therefore be the same. But if the lateral surface, in contact with it be more than twice the magnitude of the bottom, then the total pressure on the sides will be more than the whole weight of the liquid contained in the vessel, in the proportion of the lateral surface in contact with the liquid to twice the magnitude of the bottom of the vessel. Thus, if the lateral surface in contact with the liquid be ten times as great as twice the bottom of the vessel, then the lateral pressure will be ten times the weight of the liquid contained in the vessel; and so on for other proportions.

Hence it appears, that in tall narrow vessels the lateral pressure very far exceeds the downward pressure, which is equal to the weight. Tall casks or cisterns, and tubes which are carried in a vertical direction, require, therefore, to have a lateral strength very far exceeding that which would be necessary merely to support the liquid which they contained.

(25.) The increase of pressure proportionably with the depth suggests the expediency of observing a corresponding variation in the strength of the several parts of embankments, dams, flood-gates, and other resistances opposed to the course of water. The pressure near the surface is inconsiderable, and therefore a small degree of strength is sufficient in the resisting surface; but as the depth increases, the pressure increases in the same ratio. If, therefore, as in the case of dams and embankments, the strength depends upon the thickness, the latter must increase from the top to the bottom; so that while the interior surface presented to the liquid is perpendicular, the exterior surface must gradually slope, giving increased thickness to the dam towards the bottom, so that the section shall have such a form as that represented in *fig.* 13.

Fig. 13.



(26.) If the side of the vessel be straight, but not perpendicular, the pressure upon it will be determined by the same principles, and nearly in the same manner. The pressure will still be proportional to the depth, and the point of medium pressure will be a point on the side, at half the entire depth of the fluid. If, as before, the side be divided into ten equal parts, the same reasoning will be applicable; for, although the depths of the several points of division are no longer measured along the side of the vessel, yet they are proportioned to the distances of the several points of division from that

point on the side of the vessel which marks the surface of the liquid. Hence, in this case, as well as in the former, the medium pressure is that which affects the middle part of the depth marked 5. in *fig.* 14.; and the

Fig. 14.

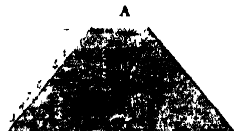


whole lateral pressure will be obtained by multiplying the number of square feet on the sides of the vessel by the number of feet in half the depth of the liquid: the product will express the number of solid feet of the liquid whose weight is equal to the total pressure.

In this manner, the pressure on inclined embankments, or the sloping sides of vessels containing liquids, may be ascertained.

In *fig.* 14. the sides of the vessel containing the liquid are represented as sloping outwards, or diverging upwards from the bottom; and it is not difficult to conceive, that each point of the side will sustain a pressure equivalent to the weight of the column of liquid perpendicularly above it: but the same consequence would ensue if the sides inclined inwards or converged upwards from the bottom, as in *fig.* 15. In this case also, al-

Fig. 15.



though each point of the lateral surface have not any column of the liquid perpendicularly over it, still it is pressed by the liquid in a direction perpendicular to the side, with the same force as if such a column were perpendicularly over it. The cause of this may be conceived by the following reasoning. Let P be a particle

of the liquid, at the same depth below the surface as the division marked 5. on the side of the vessel; this particle is evidently pressed downwards by the weight of the incumbent column PA. But, by what has been already proved, it must be pressed by the same force in every possible direction; and, therefore, it is pressed with this force from P in the direction of the division 5. on the side: this pressure is therefore transmitted to the particle contiguous to the division 5. This point, therefore, resists that pressure; and the same reasoning will apply to every other point in the side of the vessel.

From what has been just stated, it follows, that if the sides of the vessel, *fig.* 14. and *fig.* 15., be equally inclined, but in contrary directions to their bottoms, that the vessels be filled to equal depths, and that the magnitude of the lateral surfaces in contact with the water be equal, the whole pressure sustained by the sides of the vessel will be the same, although the quantities of water which they respectively contain be very different.

(27.) The pressure on the bottom of the vessel, in all these cases, depends only on the magnitude of the bottom and the depth of the liquid; and is altogether independent of the shape of the sides, and of the whole quantity of liquid in the vessel. Thus, in three vessels, shaped as those represented in *fig.* 12., *fig.* 14., and *fig.* 15., if the bottoms have the same magnitude, and the liquids contained in them the same depth, the pressure on the bottoms will be the same; viz. the weight of the liquid which would be contained in a vessel having an equal bottom and perpendicular sides. This will be evident, if it be considered that each point of the bottom is under the pressure of the column of liquid immediately above it, in the case of *fig.* 12. and *fig.* 14.; and the same reasoning may be extended to *fig.* 15., as already explained (26.).

We may hence infer generally, that the pressure upon a flat horizontal bottom is found by multiplying the number of square feet in the bottom by the number of feet in the depth of the liquid; the product will ex-

press the number of solid feet of the liquid whose weight is equal to the pressure on the bottom. In a vessel of the shape represented in *fig.* 14., the pressure on the bottom is less than the whole weight of the liquid. In a vessel such as that represented in *fig.* 15. it is greater than the weight of the liquid; and in such a one as is represented in *fig.* 12. it is equal to the weight of the liquid.

These results may be verified experimentally, by providing three vessels of the shapes already mentioned, having moveable bottoms, which, when applied to them, will be water-tight, the bottoms being equal. Let the bottom be pressed against each vessel with equal forces, which may be done by a lever, one arm of which is pressed upwards against the bottom, by a weight suspended on the other arm. Let water be now poured into each of the vessels, until by its pressure the bottom is detached. It will be observed that the depth of water in each of the three vessels necessary to accomplish this is the same.

There is another method of illustrating these theorems experimentally, which is attended with less practical difficulty than that just mentioned. Let the moveable bottom be pressed against each vessel by a string attached to it, and carried up through the vessel; and then let the vessel be plunged in a cistern of water, as represented in *fig.* 16., until it attain such a depth that the upward pressure of the water under the bottom will be sufficient to keep the bottom firmly attached to the vessel. Let the string be then disengaged, and let water be poured into the vessel until its pressure detaches the bottom; and let the depth of water be observed which is sufficient to effect this. Let each of the three vessels be immersed in the cistern in a similar way, and to the same depth, as represented in *figs.* 16, 17, and 18. It will be found that the depth of water necessary to be poured into the vessel in order to detach the bottom will be the same.

The following experiment is a very striking illustration of the same principle: —

A cylindrical vessel A B, *fig.* 19., has a glass tube

Fig. 16.

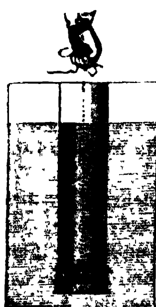
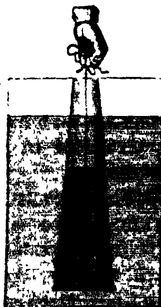


Fig. 17.

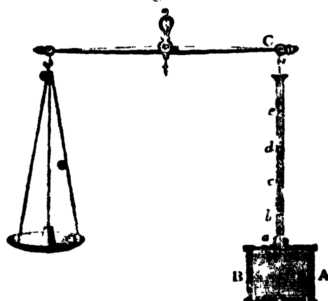


Fig. 18.



inserted in it water-tight at *a*, and is provided with a moveable bottom, which, however, fits it water-tight. This bottom is supported by a wire, which passing up the tube is attached to the arm of a balance, and is coun-

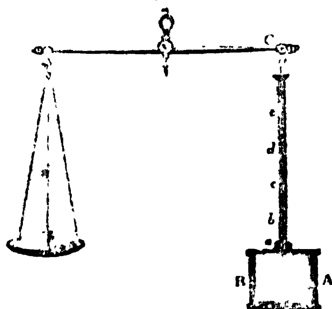
Fig. 19.



terpoised by a weight in the dish suspended from the other arm. Suppose the vessel A B now to be filled with water to the neck, *a*; and let the tube be divided into parts at *b*, *c*, *d*, *e*, each of which shall be equal to the depth of the vessel A B. Let a sufficient weight be put into the dish to maintain the bottom of the vessel A B in its place. This weight will be found to be equal to the weight of the water contained in the vessel A B.

Thus, it appears that this water presses down the bottom with a force equal to its weight. Let water be now poured into the tube until it rises to the level *b*: it will be found that exactly as much more weight in the dish D will be necessary to maintain the bottom in its place, as was required to support it when the level was at *a*. Thus, the column *a b* produces as much pressure

Fig. 19.



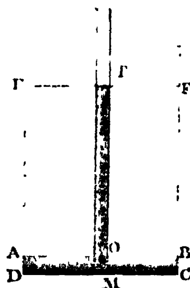
on the bottom as the whole of the liquid in the vessel A B. If the tube be again filled to the level *c*, the pressure will receive another increase, equal to the weight of the liquid contained in A B; and a similar addition must be made to the counterpoise, in order to maintain the bottom of the vessel in its place. In the same manner, each addition which is made to the column in the tube equal to the depth of the vessel A B will cause a similar increase in the pressure, and will be indicated by the necessity of giving a corresponding increase to the counterpoise.

In this case the box A B and the tube must be fixed in their position independently of the bottom of the vessel. The force which sustains the bottom will have a tendency to press the vessel A B upwards, amounting to the excess of the whole weight in the dish above the weight of the bottom of the vessel, together with the weight of the water in the vessel and tube. In fact, all that part of the weight in the dish which is not spent in

supporting the bottom and the water above it, is expended in producing a pressure against the top of the vessel A B, which that vessel must be so firmly fixed as to resist.

(28.) We have hitherto supposed the sides of the vessel to be straight and regular; but, even though they be not, the pressure on the bottom is determined by the same rules. In the consequences of this principle, the hydrostatic paradox reappears under some curious forms.

Fig. 20.



Let A B C D, *fig.* 20., be a square close vessel, with a small hole, O, in the top, in which a narrow tube, T O, is screwed water-tight. Let the vessel A B C D, and the tube to the level T, be filled with water. According to the principle which has been just established, the pressure on the bottom, C D, will be proportional to the depth, T M; or, in fact, will be equal to the weight of water which would fill a vessel of the magnitude E D C F. This will be the case, however shallow the vessel, A B C D, and however narrow the tube, T O, may be; and hence an indefinitely small quantity of water may be made to produce a pressure on the bottom of the vessel which contains it, equal to the weight of any quantity of water, however great.

As the pressure depends only on the depth, and is independent of the shape of the vessel, it is not necessary that the tube, T O, should be straight, but it may be bent or deflected into any irregular form whatsoever. But,

whatever be its shape, the depth of the fluid is to be estimated by the perpendicular distance of the upper surface from the bottom of the vessel.

(29.) In the examples already given, the sides and bottoms of the vessels considered have been flat surfaces, or have been in the perpendicular or horizontal position. The surfaces, however, of vessels or reservoirs are subject to every variety and shape; and it is necessary in practical science to possess rules applicable generally to all surfaces which contain liquids. What has been already stated with respect to the average pressure, is the principle which, generalised, must lead to such a rule. The various parts of any surface, whatever be its form, will be subject to pressures, depending on their depths below the surface of the liquid, all points at the same depths suffering the same pressure. There is a certain pressure, or mean of all the various pressures, to which the points of the surface are subject; and whatever this pressure be, it must be such, that, if diffused over the whole surface, the total amount of the pressure on that surface will not be altered. If, therefore, this medium pressure can be found, and the magnitude of the surface in contact with the liquid be known, the total pressure may immediately be obtained. Suppose, for example, the average pressure be 15 pounds upon every square inch, and that the magnitude of the surface in contact with the liquid be 100 square inches, then the total pressure will be 1500 pounds.

The determination of the total pressure, therefore, depends on that of the average pressure. Now, as the pressure at each point is proportional to the depth of that point below the surface, it may be considered as represented by that depth. Thus, if a pressure of one pound be produced upon a square inch at the depth of one foot, a pressure of two pounds will be produced upon a square inch at the depth of two feet, three pounds at the depth of three feet, and so on; the number of feet in the depth always expressing the number of pounds in the pressure. Hence, it is obvious that the average

pressure will be produced at the average depth; and, therefore, the question is reduced to the determination of the point whose depth below the surface is an average of the depths of all the points of the surface in contact with the liquid. By a singular though not unaccountable coincidence, the point which would be the centre of gravity of a thin sheet lying in close contact with the surface of the vessel, covered by the fluid, is placed at that depth below the surface which corresponds to the medium pressure. This arises from a property of the centre of gravity well known to geometers, and from which that point has been sometimes called the centre of mean distances. The centre of gravity of any surface is always placed at a distance from any plane surface, which is an average or mean of all the distances of the various points of the proposed surface from the plane surface.

(30.) To determine, therefore, the total pressure on any surface, let the position of the centre of gravity of that surface be determined by the rules established in mechanics, and let its depth below the surface of the liquid be ascertained; then multiply the number of feet in this depth, by the number of square feet in the surface of the vessel covered by the liquid: the product will express the number of solid feet of the liquid, whose weight is equal to the total pressure.

Excepting the case of regular surfaces, the determination of the centre of gravity is a problem which cannot be solved without the aid of mathematical formularies of considerable difficulty.* We shall, however, illustrate the theorem just explained by some examples, which we can render intelligible to the general reader.

Let a hollow globe be filled with a liquid through a small hole in the top. The centre of gravity of the surface of the globe is evidently at its centre; and therefore the depth of that point is half the diameter of the globe. The total pressure will, therefore, be found by multiplying the number of feet in half the diameter of the globe

* Cab. Cyc. Mechanics, chap. ix.

by the number of square feet in its surface. By the principles of geometry it is proved, that the solid contents of a globe are determined by multiplying the number of feet in half the diameter by a third part of the number of square feet in the surface. Hence it appears that the pressure on the surface of the globe is three times the weight of its contents.

If a cubical vessel,—that is, one having a square bottom and four square sides, each equal to the bottom,—be filled with a fluid, the centre of gravity of each of the four perpendicular sides will be at half the entire depth of the fluid below the surface. Therefore the pressure on each side will be found by multiplying the number of feet in half the depth by the number of square feet in the side. But the entire contents of the vessel are found by multiplying the number of feet in the entire depth by the number of square feet in any side. Hence it appears that the pressure on each of the four sides is equal to half the weight of the fluid contained in the vessel. The pressure on all the four sides is, therefore, equal to twice the weight of the fluid contained in the vessel. The pressure on the bottom has already been shown to be equal to the whole weight of the fluid; and therefore it follows, that the total pressure of the fluid on the surface of the vessel, including both the sides and bottom, is equal to three times the weight of the fluid which it contains.

Thus it appears, that a globe and a tube containing equal measures of liquid will suffer equal pressures if filled, each sustaining a pressure amounting to three times the weight of the fluid it contains.

(31.) If any body be immersed in a fluid, the pressure which its surface sustains from the surrounding liquid, is to be determined by the same rules, and according to the same methods, as are used for determining the pressure on the surface of the vessel which contains the liquid. Thus, if a globe be plunged in a liquid, the total pressure on its surface is found by multiplying the number of feet in the depth of its centre, below the sur-

face of the liquid, by the number of square feet in its exterior surface.

(32.) The two hydrostatical theorems which we have attempted to explain in this and the preceding chapter,— viz. 1. That liquids transmit pressure equally in all directions; and, 2. That the pressure produced by the weight of a liquid is proportional to its depth, — will serve to elucidate many familiar and remarkable phenomena.

If an empty bottle, or rather one containing only air, be tightly corked, and be sunk by weights attached to it, to a considerable depth in the sea, the pressure of the surrounding water will either break the bottle, or force the cork into it through the neck. On drawing up the bottle, it will be found to be filled with water, and to have the cork within it below the neck.

If the bottle have flat sides, and be square-bottomed, it will be broken by the pressure, the form being unfavourable to strength; but if it be round, it will be more likely to resist the pressure, and to have the cork forced in. The shape in this case is conducive to strength, partaking of the qualities of an arch.

An experiment of the nature just described was made by Mr. Campbell, author of "Travels in the South of Africa." On his voyage from the Cape of Good Hope homeward, he forced a cork into the neck of a bottle, so thick as to fit it very tightly, and so that half the cork remained above the edge of the neck; a cord was then tied round the cork, and fastened to the neck of the bottle; and the whole was covered with pitch. The bottle was connected with a weight to make it sink, and, being suspended by a sounding-line, was gradually let down into the sea. When it attained the depth of about fifty fathoms, an increase of weight was suddenly felt. Upon drawing up the bottle, the cork was found inside, and the bottle filled with water. The pressure of fifty fathoms of water had forced in the cork, and filled the bottle.

Another bottle was similarly corked, but a sail needle was passed through the cork across the edge of the neck,

so as to resist the passage of the cork into the bottle. Thus prepared, the bottle was again immersed to the depth of fifty fathoms, and the same sudden increase of weight was felt. Upon drawing up the bottle it was found filled with water, but the cork was not displaced. Mr. Campbell attributed this effect to the water being forced through the pores of the glass by the surrounding pressure. It is, however, sufficiently evident, that the liquid obtained admission through the more open texture of the cork. The circumstance of the cork and the pitch which covered it not being broken, arose from the perfectly equal pressure which was excited upon it in all directions.*

The equality of the pressure which a liquid exerts in all directions is demonstrated by the fact, that, to whatever depth a soft or brittle substance may be immersed, it will undergo no change of shape by the surrounding pressure. This is an effect which it is obvious could not be produced by any other cause than a perfect equality of pressure on every part; for if any part were subject to a greater force than an adjacent part, that part would be pressed inwards if the body were soft, and would be broken off if it were brittle. A piece of soft wax, or a piece of glass not having any hollow part within it, being immersed to any depth in water, suffers no change.

If a piece of wood which floats on water be forced down to a great depth in the sea, the pressure of the surrounding liquid will be so severe, that a quantity of water will be forced into the pores of the wood, which will be sufficient to increase its weight, so that it will be no longer capable of floating or rising to the surface.

A diver may, with impunity, plunge to certain depths in the sea; but there is a limit of depth beyond which he cannot continue to live under the pressure to which he is subject. For the same reason, it is probable that there is a depth below which fishes cannot exist.

(33.) Liquids in general are treated in hydrostatics as incompressible bodies; that is, as bodies which being sub-

* Campbell's Travels, p. 507. Brewster's Ency. xi. p. 483.

mitted to pressure will not suffer their dimensions to be diminished; and this is true, except in extreme cases. It was long considered that no force whatever was capable of compressing a liquid; but experiments, instituted in the year 1761 by Canton prove, that under severe pressure they suffered a slight diminution of bulk: it also appeared, that upon the pressure being removed they resumed their former dimensions. It was thus established, that liquids not only were compressible in a slight degree but also elastic.*



Fig. 21.

The pressure of liquids at great depths below the surface, furnish an easy method of verifying by experiments these results. Let AB, *fig.* 21., be a cylindrical vessel, having a round hole, C, in the top, through which a piston, PM, passes water-tight. Let this vessel be completely filled with water, the piston PM being inserted in it. Let a ring slide upon the piston, with sufficient friction to prevent it from falling by its own weight; and let it be pressed down to the orifice C. Let the vessel now be plunged to a considerable depth in the sea. Upon drawing it up, it will be found that the pressure of the surrounding water had forced the piston to a greater depth in the vessel; and that the water contained in it was therefore compressed into smaller dimensions. This will be indicated by the position of the ring which slides on the piston; for that will be found not at the orifice, as before immersion, but at a certain distance above it. On being forced into the vessel, the piston passed through the ring, which was restrained in its position by the top of the vessel immediately surrounding the piston. Upon drawing up the vessel, the removal of the pressure enabled the water contained in it to resume its dimensions, and the piston was forced back to its first position In rising out of the vessel it carried the ring up with it, so that the distance of the ring from the hole C, after

* Cab. Cyc. Mechanics, p. 24.

the vessel had been drawn up, showed the space through which the piston had been forced in.

This is the most convenient practical proof of the compressibility of water. It likewise establishes the elasticity of that liquid; for if it were merely compressible, without being elastic, the piston when forced into the vessel would remain in it, and the water compressed would continue to retain its diminished volume after the force which compressed it had been removed.

The degree of compression produced by a given force, may be found by determining the total contents of the vessel; the magnitude of a given length, as one inch of the piston; the depth in the vessel to which the piston has been forced, and the depth in the sea to which the vessel has been sunk. At the depth of 1000 fathoms, it has been found that the bulk of the water contained in the vessel is diminished by one twentieth of its original dimensions. Thus, 20 solid inches of water will be reduced, by the pressure of 20 fathoms of sea water, to 19 solid inches.

(34.) If a fissure in a rock happen to communicate with an internal cavity of any considerable magnitude, placed at some depth below the top of the fissure, it may happen that rain, percolating through the fissure, and thereby filling the internal cavity, shall split the rock. The pressure acting against the surface of the cavity, and tending to burst the rock, will in this case be proportional to the depth of the cavity below the top of the fissure. For every 28 inches in this depth, a pressure of about one pound will be produced upon every square inch of the surface of the cavity.

(35.) In the construction of pipes for the supply of water to cities, it is necessary that those parts, which are much below the level of the reservoir from which the water is supplied, should have a greater strength than is requisite in those which are in more elevated situations. A pressure always acts upon the inner surface of the pipe tending to burst it, which may be estimated in the manner already explained. A pipe, the diameter of whose

bore is 4 inches, has an internal circumference of about 1 foot, and the internal surface of 1 foot of such a pipe will be 1 square foot, or 144 square inches. If such a pipe were 140 feet below the level of the reservoir, it would therefore suffer a bursting pressure, amounting to about 60 pounds on every square inch of its surface. for 28 inches is contained 60 times in 140 feet; and hence a piece of the pipe 1 foot long will sustain 144 times this pressure, that is, a bursting pressure of 8640 pounds. This pressure considerably exceeds that which is produced in most high pressure steam engines.

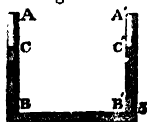
CHAP. IV.

LIQUIDS MAINTAIN THEIR LEVEL.

EXPERIMENTAL PROOFS. — VESSEL CONNECTED WITH COMMUNICATING TUBE. — SEVERAL VESSELS BETWEEN WHICH THERE IS A FREE COMMUNICATION. — HYDROSTATIC PARADOX EXPLAINED BY THIS PRINCIPLE. — SURFACE OF A LIQUID LEVEL. — WHY THE QUALITY DOES NOT EXTEND TO SOLIDS. — SURFACE OF THE LAND. — SURFACE OF THE SEA. — CURIOUS OPTICAL DECEPTION IN WAVES. — SIMILAR PROPERTY IN REVOLVING SCREW. — ORNAMENTAL FOUNTAINS, CLOCKS. — PHENOMENA OF RIVERS, SPRINGS, WELLS, CATARACTS, EXPLAINED. — CANALS, LOCKS. — METHOD OF SUPPLYING WATER TO TOWNS. — EXACT SENSE OF THE WORD LEVEL. — COMMON SURFACE OF TWO LIQUIDS IN THE SAME VESSEL. — LEVELLING INSTRUMENTS. — SPIRIT LEVEL.

(36.) From the two properties of liquids established in the last two chapters, a third, and not less important one, may be deduced. If the pressure arising from the weight of a liquid be proportional to the depth, and that pressure be transmitted equally in every possible direction, it will follow, that the surface of all parts of a liquid contained in the same vessel, or in two or more vessels between which there is a free communication by tubes or pipes, or otherwise, must be always *at the same level;* and that if any external cause accidentally disturb that level, the liquid will by its gravity return to it, the higher parts falling, and the lower parts rising, until the equality be restored.

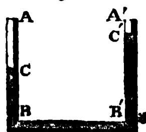
Fig. 22.



Let A B and A′ B′, *fig.* 22., be two perpendicular glass tubes, united by a third tube, B B′, placed in a horizontal position. Let any liquid be poured into the tube A until the horizontal tube B B′ is filled. Let us now suppose that the lower end of the tube A′ B′ is closed by a stopcock at B′. The tube B B′ being horizontal, the water

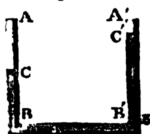
which fills it has no tendency to move by its weight towards either end, and therefore the stopcock at B′ sustains no pressure from it. Let an additional quantity of the liquid be now poured in at A until it fill the tube to the height C. The surface of the liquid in the horizontal tube at B is now pressed by the weight of the column BC. The liquid in the horizontal tube transmits this pressure undiminished to the stopcock B′, which is therefore pressed upwards by a force equal to the weight of the column of liquid BC. This pressure would evidently cause the liquid in the horizontal tube to rush into the vertical tube B′C′ if the stopcock B′ were opened. Supposing it to remain closed, however, let a quantity of the liquid be poured in at A′ until the column B′C′ shall attain the same height as the column BC; the stopcock B′ will then be pressed downwards by the weight of the column B′C′ resting upon it, while it is at the same time pressed upwards by the weight of the column B C, transmitted to it by the liquid in the horizontal tube. It is thus pressed upwards and downwards by equal forces; and therefore, if it were free to move, it would have no tendency to change its position: hence, if the stopcock B′ be opened, and the column B′C′ allowed to rest immediately on the surface of the liquid, it will be supported, and no motion will take place; thus the columns B C and B′C′, having equal heights, balance each other through the medium of the liquid in the horizontal tube.

Fig. 23.



Let us suppose the stopcock B′, *fig.* 23., again closed, and let the column of liquid in B′A′ be greater than the column of liquid in BA, so that C′ will be higher than C. The stopcock at B′ will now be pressed downwards by the weight of the column B′C′, and it will be pressed upwards by the weight of the column B C. The downward pressure being therefore greater than the upward, if the stopcock be opened, the column B′C′ will descend, and the column B C will be forced up. The level C′

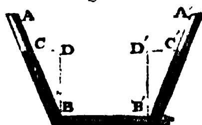
Fig. 23.



will therefore fall, and the level C will rise. When they attain the same height, their weights will mutually balance each other, as in *fig.* 22.; and if these were the only forces in action, all motion would then cease. But in the descent of the column B′ C′ the whole mass of liquid in the tubes has acquired a certain velocity, which, by reason of its inertia*, it has a disposition to retain. The level C will therefore continue to rise, and the level C′ to fall, after they have attained the same height; but when the column B C becomes higher than B′ C′ its downward pressure exceeds the upward pressure transmitted to it from B′C′, and this excess resists the tendency to continue its motion upwards, and finally destroys it. The level C will then begin to descend, and the level C′ to rise; and this will continue until the level C′ has attained the height which it had at the commencement of the process; it will then fall, and the oscillation will continue.

We have here, however, set aside the consideration of the effects of the friction between the liquid and the tubes which contain it. This, by continually resisting the motion of the liquid, will cause it to rise to a less height in the tubes, at each oscillation, than it did at the preceding one, and at length will reduce it to a state of rest. In this state the surfaces C C′ will be at equal heights above the horizontal tube B B′.

Fig. 24.



(37.) We have hitherto supposed the tubes A B and A′ B′ to be perpendicular, but the same consequences will ensue if they have any oblique position, as in

* Cab. Cyc. Mechanics, p. 28. *et seq.*

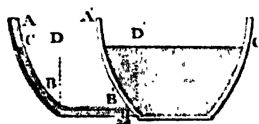
fig. 24. As before, let a stopcock be placed at B′ and closed; let the horizontal tube B B′ be filled with liquid, and let a column be also poured into the oblique tube A B, the surface of which is at C. According to what has been proved in the last chapter, the column B C presses on the liquid in the horizontal tube with a force proportioned to the perpendicular height of the surface C above B. In fact, it presses with a force equal to the weight of a column whose height is B D, the line drawn from B perpendicular to the horizontal line from C. This pressure, therefore, is transmitted by the liquid in the horizontal tube to the stopcock B′, which is pressed in the direction of the tube B′ A′ with that force. If a quantity of liquid be now poured in at A′, until the height of the surface C′ above B′ be equal to the height of the surface C above B, the downward pressure on B′ will be equal to the upward pressure transmitted from the column B C; for this downward pressure is equal to the weight of a column whose height is B′ D′, which is equal to B D.

By reasoning precisely similar to that which has been used with respect to the perpendicular tubes, it may be proved, that if the stopcock B′ be opened, the liquid will remain at rest; and also that if the surface C′ be not at the same level with the surface C, an oscillation will take place, which being continued for a certain time, the surfaces will at length settle at the same height above the horizontal tube.

(38.) We have hitherto supposed that the tubes containing the liquid, whose weight produces the pressure, are equal in bore. The same consequences may, however, be deduced, if they be unequal, or if, instead of being tubes, they be vessels of any form whatever. Let A B, *fig.* 25., be an oblique tube communicating with a reservoir A′ B′, a stopcock being placed at B′. Let the tube and reservoir be now filled to the same height, C C′, the stopcock at B′ being closed. The same horizontal line, C C′, will mark the level of the liquid in the

tube, and the liquid in the reservoir. The liquid B C, in the tube B A, will press on the liquid in the horizontal tube, with a force equal to the weight of a column of the liquid whose height is B D, and whose base is equal

Fig. 25.

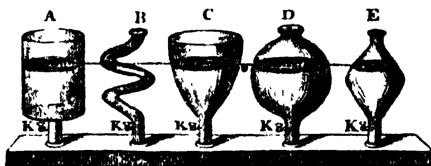


to the section of the tube at B. This force will be transmitted by the liquid in the horizontal channel B B′, so that each square inch of the surface of the stopcock B′ will be pressed by a force equal to the weight of a column whose base is a square inch, and whose height is equal to B D. The liquid in the vessel A′ B′ presses on each square inch of the other side of the stopcock, with a force which is equal to the weight of a column whose base is a square inch, and whose height is B′ D′. If therefore, as we have already supposed, B′ D′ be equal to B D, the stopcock will be pressed equally on both sides; and if it be opened, no motion will take place in the liquid. But if, on the other hand, B′ D′ be not equal to B D, the higher surface will subside, and the lower one rise, and the oscillating motion already described will ensue, and will continue until, at length, the surfaces C and C′ settle at the same level.

An apparatus, to illustrate experimentally the property by which liquids maintain the same level in communicating vessels, is represented in *fig.* 26. A, B, C, D, E, are glass vessels, of various shapes, communicating by short tubular shanks with a horizontal tube, which passes beneath them, and which in the figure is concealed by the stand which supports the vessels. In the shank of each is placed a stopcock, K, which when closed insulates the vessels, and when opened leaves a free communication between them by means of the tube. Let all the stopcocks be now closed, and let water be poured into

the several vessels, so as to stand at different heights: if the several stopcocks be opened, so that the vessels shall have a free communication with each other, the higher surfaces will fall, and the lower ones rise, until

Fig. 26.



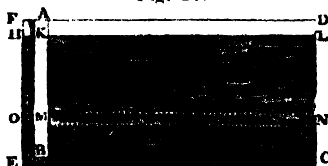
they attain the same level, and then all motion will cease. If the stopcocks be again closed, and water poured into the vessels, so as to give the liquids different levels, the experiment may be repeated by opening the stopcocks. It will always be found, that, when the stopcocks are opened, the liquid will settle itself to the same level in all the vessels.

A teapot, kettle, or any other vessel containing a liquid, and having a spout, must be so constructed that the lip of the spout shall be on a level with the top of the vessel, or at least on a level with the highest point to which the vessel is to be filled; otherwise, upon filling the vessel above the level of the end of the spout, the liquid in the vessel, having a tendency to rise above the level of the end of the spout, will issue from it. If the vessel be inclined with the spout downwards, it takes a position in which the level of the water in the vessel is above that of the lip of the spout, and accordingly the liquid flows out.

(39.) Various examples of that class of effects which have been called the Hydrostatic Paradox, and which have been already noticed, may be shown to be equivalent to this property by which fluids maintain their level. We shall confine ourselves here to one example. Let

A B C D, *fig.* 27., be a large vessel, with perpendicular sides, and communicating by B E with a perpendicular tube, E F. If water be poured into A B C D until it rises to the level K L, it will stand at the same level, H, in the tube E F.

Fig. 27.



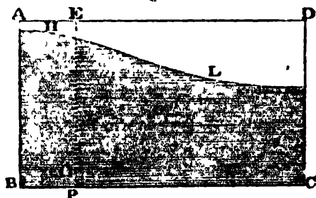
Now, suppose all the water in the vessel A B C D above the level M N to be removed, and its place supplied by a piston, M N, which moves watertight in the vessel; and let this piston be loaded with weights, so that the weight of itself and its load shall be equal to the weight of the water which has been removed: the piston will then press on the water below it with the same force as the water removed previously pressed upon it; and as the water removed was sustained by it, the piston with its load will also be sustained. Thus it appears, that this piston is supported by the pressure of the column of water in E F. It will easily be perceived that this is identical with the hydrostatic bellows explained in (8.).

If the column of water in the tube above the level O be removed, and its place supplied by a piston of equal weight, this piston, O, will support the great piston M N. This effect is equivalent to the principle of the hydrostatic press explained in (7.).

(40.) After what has been already proved, it is nearly self-evident that every part of the surface of a fluid confined in a vessel must, if at rest, be at the same level. If this were not the case, it would evidently be possible that the surfaces of the same fluid, in communicating vessels, might have different levels; for if we suppose two different parts of the surface of a liquid in a vessel

to have different heights, as represented in the vessel ABCD, *fig.* 28., let us divide the vessel into two by a solid partition, EP, leaving, however, between the two

Fig. 28.



parts, a communication, O, at the bottom; and let this partition so divide the liquid, that the higher part of the surface, H, shall occupy one division, and the lower part, L, the other. We should thus have a liquid in communicating vessels standing at different levels; a result which would be inconsistent with what was formerly proved. Therefore it follows, that all parts of the surface of a liquid contained in any vessel must stand at the same level when at rest.

Indeed, this theorem is nothing more than a manifestation of the tendency of the component parts of every body to fall into the lowest position which the nature of their mutual connection, and the circumstances in which they are placed, admit. Mountains do not sink and press up the adjacent valleys, because the strong cohesive principle which binds together the constituent particles of their masses, and those of the earth beneath them, is opposed to the force of their gravity, and is much more powerful: but if this cohesion were dissolved, these great elevations would sink from their lofty eminences, and the intervening valleys would in their turn rise—an interchange of form taking place; and this undulation would continue until the whole mass would attain a state of rest, when no inequality of height would remain. All the inequalities, therefore, observable on the surface of land, are owing to the predominance of the cohesive over the gravitative principle: the former

depriving the earth of the power of transmitting, equally and in every direction, the pressure produced by the latter.

On the other hand, if the sea, when in a state of agitation, were suddenly congealed, the cohesive principle taking a strong effect, the mass of water would lose the power of transmitting pressure, and those inequalities which, in the liquid form, were fluctuating, would become fixed; every wave would be a hill, and the intermediate space a valley.

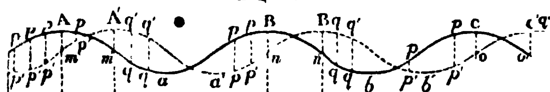
There is a curious optical deception attending the alternate elevation and depression of the surface of a liquid, which it may be useful here to notice. The waves thus produced appear to have a progressive motion, which is commonly attributed to the liquid itself. When we perceive the waves of the sea apparently advancing in a certain direction, we are irresistibly impressed with a notion that the sea itself is advancing in that direction. We consider that the same wave, as it advances, is composed of the same water, and that the whole surface of the liquid is in a state of progressive motion. A slight reflection, however, on the consequences of such a supposition, will soon convince us that it is unfounded. The ship which floats upon the waves is not carried forward with them; they pass beneath her, now lifting her on their summits, and now letting her sink into the abyss between. Observe a sea fowl floating on the water, and the same effect will be seen. If, however, the water itself partook of the motion which we ascribe to its waves, the ship and the fowl would each be carried forward, and would have a motion in common with the liquid. Once on the summit of a wave, there they would continually remain, and their motion would be as smooth as if they were propelled upon the calm surface of a lake. Or if once in the valley between two waves, there likewise they would continually remain, the one wave continually preceding them and the other following.

In like manner, if we observe the waves continually

approaching the shore, we must be convinced that this apparent motion is not one in which the water has any share: for were it so, the waters of the sea would soon be heaped upon the shores and would inundate the adjacent country: but so far from the waters partaking of the apparent motion of the waves in approaching the shore, this motion of the waves continues, even when the waters are retiring. If we observe a flat strand when the tide is ebbing, we shall still find the waves moving towards the shore.

That the apparent motion of the waves is, therefore, an illusion, we can no longer doubt; but we are naturally curious to know what is the cause of this illusion. That a progressive motion takes place in *something*, we have proof, from the evidence of sight. That no progressive motion takes place in the liquid, we have also proof, both from the evidence of sight, and from other still more unquestionable testimony. To what then does the motion belong? We answer, to the *form* of the wave, and not to the liquid which composes it.

Fig. 29.

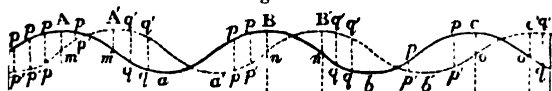


L K K' M

Let the undulating line in *fig.* 29. be supposed to represent the surface of the sea, and let A B C be the crests of three successive waves, and *a b c* the intermediate valleys: let L M represent the bottom of the sea. At A, the depth of the water is represented by the line A K. Take any point near A, as *m'*, and the depth here is represented by *m'* K'. The summit of the wave being A, the depth at A is greater than the depth at *m'*. The pressure of the column A K being greater than that of *m'* K', the point A has a tendency to fall, and the

point *m′* to rise by reason of this excess of pressure. Therefore *m′* will rise to the point A′, while A sinks to the level *m*. Thus the points A and *m′* have interchanged levels; the point *m′* being now raised to as great a height above the bottom L M as the point A had

Fig. 29.



before the change, and the point A having fallen to the height which *m′* had. In like manner it will be found that, for every point in the first position of the wave, there is another point in the second position with which it interchanges elevations. If these circumstances be closely considered, it will not be difficult to perceive that, in the interval which we have supposed, the various points on the surface of the water, such as *m′*, which were before on the sloping sides of the waves, have now become their summits, A′B′C′, &c. Not that the points A B C, &c. have advanced to A′B′C′, &c., but that they have fallen from their former elevations, while the latter have risen. It appears, therefore, that the undulations of the surface are produced by its different points ascending and descending alternately in a perpendicular direction, without any kind of progressive motion.

To make this still more clear, let us suppose that perpendicular lines be drawn from every part of the surface A *a* B *b* C *c*, &c. to the corresponding points in the surface A′ *a′* B′ *b′* C′ *c′*, &c., and let the interval between the periods at which the surface of the liquid assumes these two forms be conceived to be one second; in that time the several points of the first surface, which are marked by the letters *p*, fall in the direction of the dotted lines perpendicularly downwards to the points marked *p′*,

and the points marked *q* rise perpendicularly upwards, in the directions marked by the dotted lines, to the positions indicated by the letters *q'*. Between the two positions A and A', the points of the surface between A and *m'* have both risen and fallen during the second; they have first risen to an elevation equal to that of A, and have for an instant in their turn formed the crest of the wave; but, before the expiration of the second have again fallen perpendicularly to their position in the dotted line. It will thus, it is hoped, be understood how the *form* of a wave may actually have a progressive motion, while the water which composes it is stationary.

If a cloth be loosely laid over a number of parallel rollers at such a distance asunder as to allow the cloth to fall between them, the shape of waves will be exhibited. If a progressive motion be now given to the rollers, the cloth being kept stationary, the progressive motion of waves will be produced,—the cloth will appear to advance.

It is the same cause which makes a revolving corkscrew, held in a fixed position, seem to be advancing in that direction, in which it would actually advance if the worm were passing through a cork. That point which is nearest to the eye, and which corresponds to the crest of the wave in the former example, continually occupies a different point of the worm, and continually advances towards its extremity.

This property has lately been prettily applied in ornamental clocks. A piece of glass, twisted so that its surface acquires a ridge in the form of a screw, is inserted in the mouth of some figure designed to represent a fountain. One end of the glass is attached to the axle of a wheel which the clockwork keeps in a state of constant rotation, and the other end is concealed in a vessel designed to represent a reservoir or basin. The continual rotation of the twisted glass produces the appearance of a progressive motion, as already explained, and a stream of water continually appears to flow from the fountain into the basin.

(41.) The properties in virtue of which liquids maintain their level, and transmit pressure, are the cause of most of the phenomena exhibited in the various motions and changes to which water is subject on the surface of the earth. The rain which falls on the tops of mountains and other elevated places, if it encounter a soil not easily penetrable by water, collects in rills and small drains, which, soon uniting, form streams and rivulets. These descending along the sides of the elevations, seeking a lower level, gradually encounter others, with which they unite, and at length swell into a river. The waters still having a tendency to descend, are governed in their course by the slopes of the ground over which they have to pass. They usually proceed in a winding channel, directed by the varying form of the surface of the country, always taking that course which most accelerates their descent. Sometimes they widen and spread into a spacious area, which, losing the character of a river, is denominated a lake; again contracting, they resume their former character; and after being swelled and increased by tributary streams, they at length come to their final destination, and restore to the ocean those waters which had originally been taken from it by evaporation. Throughout the whole of this process the only principle in operation is the tendency of liquid to find its level.

In some cases, the rain which is lodged on elevated grounds meets a soil of a spongy and porous nature, or one which by various crevices and interstices is pervious by water. In such cases the liquid often passes to very great depths before it encounters a barrier formed by an impenetrable stratum. When it does, and is confined, it is subject to a considerable hydrostatic pressure from the water which fills the more elevated veins and channels by which it is fed. This pressure frequently forces the water to break a passage through the surface, and it gushes out in a spring, which ultimately enlarges into a tributary stream of some river. In some cases, the water which is filtered through the earth is confined by impenetrable barriers in subter-

raneous reservoirs; barriers, the strength of which exceeds the hydrostatic pressure. If the ground perpendicularly above such a barrier be opened, and a pit sunk to such a depth as will penetrate those strata of the earth which are impervious to water, the liquid in the subterraneous reservoir, having then free admission to the pit, will rise in it until it attain the level which it has in the channels from which it is supplied. If this level be above the surface of the ground, it will have a tendency to rush upwards and if restrained by proper means, may be formed into a *fountain*, from which water will always flow by simply opening a valve or cock. If the level of the source be nearly equal to that of the mouth of the pit, the water will rise to that level, and there stand: it will form a *well*. If the level of the source be considerably below the mouth of the pit, the water will not rise in the pit beyond a certain height corresponding to the level of its source. In this case, a *pump* is introduced into the pit, and the water is raised upon principles which will be explained when we come to treat of pneumatics.

The water collected in the earth in this manner by infiltration, sometimes bursts its bounds and rushes into the bed of the sea. It is stated by Humboldt, that at the mouth of the Rio los Gartos there are numerous springs of fresh water at the distance of 500 yards from the shore. Instances of a similar kind occur in Burlington Bay on the coast of Yorkshire, in Xagua in the island of Cuba, and elsewhere.

Those sublime natural objects, cataracts and waterfalls, are manifestations of the tendency of liquids to maintain their level. When by the union of streams large quantities of water are collected at elevations considerably raised above the level of the sea, the river whose head is thus formed frequently encounters, in its approach to the sea, abrupt declivities, down which it is precipitated in a cataract. The heights of the cataracts of the great rivers of the world, though commonly much exaggerated, are still such as to place these tremendous

phenomena among the most appalling of natural appearances. The celebrated cataract of TEQUENDAMA, formed by the Rio Bogota, in South America, was long considered to be the highest in the world, the fall having been estimated by Bouguer to be not less than 1500 perpendicular feet. Humboldt, however, has more recently found this calculation to be erroneous, and has shown that the height of the fall does not exceed 600 feet.* The stream before it approaches the precipice has a breadth of 140 feet, which immediately contracts, and at the edge of the abyss is reduced to 35 feet. The great cataracts of Niagara are well known; the breadth of the stream is 400 yards immediately before the descent, and the liquid is precipitated through the perpendicular height of 150 feet. The sound of this cataract is distinctly audible at a distance of thirteen miles.

The motion of water in rivers has a sensible effect in wearing away their beds. By this means, in the course of time, the face of a country may undergo considerable changes. The falls of Niagara are gradually changing their aspect by this cause; and it is probable that a period will come, when the bed of the stream between these falls and Lake Erie will be worn to a depth such as to drain the entire of the waters of that inland sea, and convert the space it now occupies into a fertile plain.† Such a change appears to have been already produced at the falls of the Nile Syene, which are not at all conformable to what we learn from the ancients to have existed there in former times.

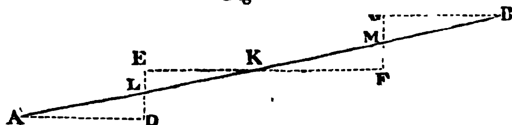
In accomplishing their descent to the level of the ocean, rivers sometimes suddenly disappear, finding through subterranean caverns and channels a more precipitate course than any which the surface offers. After passing for a certain space thus under ground, they reappear, and flow in a channel on the surface to the sea. Sometimes their subterraneous passage becomes choked, and they are again forced to find a channel on the sur-

* Humboldt's Researches, vol. i. p. 76.
† Brewster's Edinburgh Encyclopedia, vol. xvi. p. 519.

face. The waters of the Oronoko lose themselves beneath immense blocks of granite at the Raudal de' Cariven, which, leaning against one another, form great natural arches, under which the torrent rushes with immense fury. The Rhone disappears between Seyssel and Sluys. In the year 1752, the bed of the Rio del Norte, in New Mexico, became suddenly dry to the extent of 60 leagues; the river had precipitated itself into a newly formed chasm, and disappeared for a considerable time, leaving the fine plains upon its banks entirely destitute of water. At length, after a lapse of several weeks, the subterraneous channel having apparently become choked, the river returned to its former bed. A similar phenomenon is said to have occurred in the river Amazon, about the beginning of the eighteenth century. At the village of Puyaya, the bed of that vast river was suddenly and completely dried up, and remained so for several hours, in consequence of part of the rocks near the cataract of Rentena having been thrown down by an earthquake.*

(42.) The methods of conducting a canal through a country depend upon this property, by which liquids find their level: when the space through which the canal is to be conducted is not a uniform level plain, the effects of its declivity are provided against by contrivances called *locks*. If a canal were cut upon an inclined surface, the water would run towards the lower extremity, and overflow the bank, leaving the higher end dry. A channel of any considerable length, even with a gentle and gradual slope, would be attended with this effect.

Fig. 30.

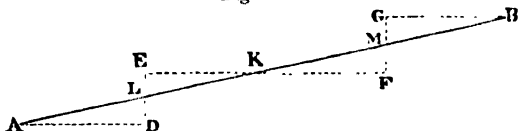


The course of the canal is therefore divided into levels of various lengths, according to the inequalities of the country through which it passes. Let A B, *fig.* 30.,

* Brewster's Edinburgh Encyc. vol. xvi. p. 519. Humboldt, vol. ii. p. 512.

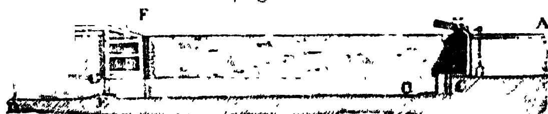
represent a slope, along which it is required to conduct a canal. A series of levels, A D, E F, G B, are constructed artificially, partly by forming mounds, L E K

Fig. 30.



and M G B, and partly by excavations, A D L and K F M. The canal is carried successively along each of the levels B G, F E, D A. These communicate with each other by locks at E D and G F, by means of which vessels passing in either direction are raised or lowered with perfect ease and safety.

Fig. 31.



The construction of a lock is easily understood. Let A B and C D, *fig.* 31., be two adjacent levels of a canal; the water in the higher level, A B, is confined by a floodgate, B C, which may be opened and closed at pleasure, and near the bottom of which are small openings, covered by sliding boards, through which water in the higher level may be allowed gradually to flow into the lower one. Suppose C E a length sufficient to contain the vessels which are to pass the lock; at E let another floodgate be placed, carried to a height equal to the level of the water in A B. If a vessel is to be passed from the higher level to the lower, the floodgate F G is closed, and the sluices at the bottom of B C are opened. The water flows from these into the lock B G, and continues to flow until it attains the same level in the lock and in A B. The gate B C is then opened, and the vessel is drawn from A B into the lock. The gate B C is then closed, and the sluices at the bottom of F G are

opened. The water begins to flow from the lock into E D, and the level of the water in the lock gradually subsides. The vessel floating upon it is thus slowly lowered; and this continues until the water in the lock attains the same level as the water in E D. The gate F G is then opened, and the vessel is drawn out of the lock into the lower level.

A vessel is conducted from the lower to the higher level by the reverse of this process. The gate B C being closed, and the gate F G opened, the water in the lock and in E D stands at the same level. The vessel is drawn into the lock, and the gate F G closed. The sluices in B C are opened, and water permitted to pass gradually from the higher level into the lock; the surface of the water in the lock is thus slowly elevated, raising the vessel with it; and this continues until its surface attain the level of the water in A B. The gate B C is then opened, and the vessel drawn into the higher level.

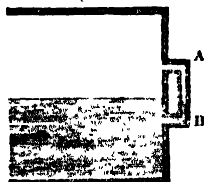
In whichever direction a vessel pass through a lock, it is evident that a quantity of water sufficient to raise the level of the water in the lock to that of the higher level must pass from the higher to the lower level; the canal must, therefore, be always fed with a sufficient quantity of water to supply this waste. The objections to locks are the delay they occasion and the expense of their construction, their repairs, and their attendance. It is therefore often better, where it can be accomplished, to carry the canal through a circuitous course, than to take a shorter route with a greater number of locks.

Owing to the small quantity of friction which exists between the particles of a liquid and a solid, the slightest inclination in the channel is sufficient to cause the water to flow. In a straight and smooth channel a descent of one foot in about four miles will cause the stream to flow at the rate of three miles an hour. The average slope of the principal rivers of the world is, however, greater than this.

(43.) It is necessary at all times to know the level of

the water in the boiler of a steam engine; but that being a close vessel formed of metal, it is impossible by any external indication to perceive the water within. A glass tube, A B, *fig.* 32., is inserted in the side of the boiler;

Fig. 32.



one end, A, passes into the boiler near the top, and the other end, B, near the bottom. The water in this tube must always stand at the same level with the water of the boiler; and the tube being of glass, this level may always be observed. The indication of the tube would not in this case be correct, if the upper end A were not inserted in the boiler, but left open to the atmosphere. The surface of the water in the boiler is subject to the pressure of the steam, which is there confined; and in order that the surface of the water in the tube should have the same level, it must be subject to the same pressure. This will necessarily be the case, if the top of the tube communicate with the steam by being inserted in the boiler at A.

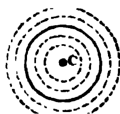
(44.) The method of supplying water for towns depends on the property of maintaining its level; a reservoir is selected in some situation more elevated than those places to which the water is to be supplied. This reservoir is fed either from natural sources or by mechanical power. Pipes are conducted from it, usually under ground, through all parts of the town; and from the main pipes smaller ones ramify, and pass into each house. These pipes may be carried in any direction which may be desirable, and alternately up and down the steepest hills, and to the tops of the highest houses, providing that the level of the water in the reservoir be above the highest points to which the pipes are carried.

By such means a constant and abundant supply of water for domestic purposes may be introduced into the upper apartments, and when used may be carried off by waste pipes.

Ignorance of this principle, by which liquids return to their level, is shown in the construction of aqueducts by the ancients for supplying water to towns. If it were requisite to conduct water across a valley, a bridge was constructed on arches, supporting a canal through which the water was carried. A pipe conducted under ground across the valley would have served the same end, with far less expense; for the water would rise as high in the pipe on the one side as it had descended on the other.

(45.) Taken in a loose popular sense, the term "level" is easily comprehended; it is necessary here, however, to explain its import more exactly. The figure of the earth is that of a globe, or nearly so; there are inequalities on its surface, but they are so insignificant, that, when compared with its own magnitude, the most enormous mountains resemble imperceptible particles of dust, resting on those globes which are used to represent the earth, and on which its natural and political divisions are depicted. These inequalities, small as they are, cease to exist on the surface of the waters when they are not agitated by wind. They present, in that case, a surface uniformly curved, and which, if continued in every direction without interruption, would assume that figure which is ascribed to the earth. If a line be drawn from the centre of the earth to any part of this surface, that line will represent the direction in which the attraction of gravity acts. It will be the direction in which a plumb-line will hang when at rest; and the surface of

Fig. 33.



the earth, such as it has been just described, will be every where perpendicular to lines thus drawn. Below and above the actual surface of the earth, other concentrical surfaces may be conceived as represented in *fig.* 33. by the dotted circles.

Each of these surfaces will enjoy the same properties as have been already ascribed to the surface of the earth. Each of them will be every where perpendicular to straight lines diverging from the centre, and will be every where equally distant from that point.

Every part of each of these concentrical surfaces is said to form the "same level;" and one level is said to be "above" or "below" another level, according as it is more or less distant from the centre.*

When a liquid mass placed upon the earth is quiescent, every part of its surface settles itself in the same level, and all parts which are disposed in any other level under its surface are subject to the same pressure; that pressure being great in proportion to the depth of the level in question below the surface.

(16.) Notwithstanding the globular form of the earth, a sheet of water on a calm day appears to exhibit a plane surface, no curvature whatever being perceivable. The cause of this is easily discovered in the small proportion which such a surface bears to the whole earth. Let us suppose a circular lake of four miles in diameter, and conceive a straight line to be drawn, or a cord stretched across it, between two opposite points. By reason of the curvature of the surface, this cord would be under the water towards the middle, if it only touched the water at the extremities; and its depth would be greatest at the centre of the lake. Nevertheless, in the case we have supposed, its depth at that point would only be $15\frac{3}{4}$ inches; the curvature, therefore, in a circuit of two miles round a given point, will not raise that point 16 inches above the plane surface, passing through the extreme points of the circuit.

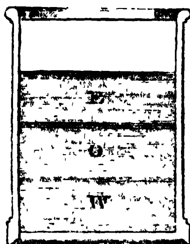
It is not wonderful, then, if fluid surfaces of small extent appear to be, and practically speaking really are, plane, the degree of curvature being insignificant. Any plane surface of a small extent is, then, said to be level, when it is parallel to the surface of a liquid which is quiescent; and all particles of a liquid which are disposed

* The concentrical surfaces are expressed in French authors by the term "couches de niveau."

in the same plane, parallel to its surface, are said to be in the same levels.

Although, as we have just stated, the curvature of the surface of a liquid be very small, yet, if that surface have sufficient extent, the curvature may be ascertained by observation. When a distant vessel first comes within sight at sea, the point of the mast only is perceived; as it approaches the mast gradually rises; and last of all appears the hulk, which, from its magnitude, would be the first seen, if the swelling curve of the surface of the sea had not obstructed the view of it.

Fig. 34.

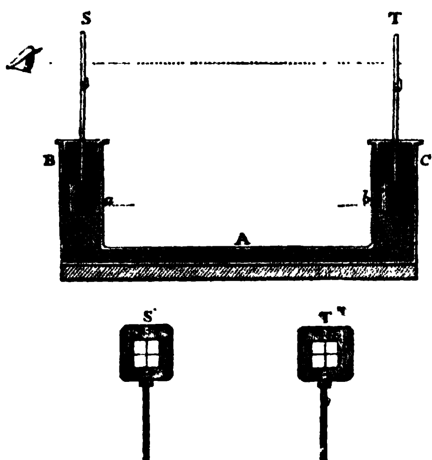


(47.) The law, by which all parts of the surface of the same liquid rest in the same level, will not be violated if one liquid be placed upon another, or even if a series of liquids were placed one above another. If a glass vessel, *fig.* 34., be partly filled with water, W, and on the water, oil, O, be poured, the surface of the water will continue to be level, bearing the oil upon it. Again, if another liquid, as ether, E, be poured upon the oil, the surface of the oil on which the ether rests will continue to be level; and so on. In these cases, however, the pressure of the liquids on any stratum is not proportional to the depth of the stratum. The pressure at any level is equal to the weight of the incumbent column of liquid. But that column is not, as in the cases formerly considered, composed of the same liquid, and, therefore, it is not true that any part of the column has a proportional weight.

The various appearances produced in ornamental water-

works are the effects of pressure transmitted through pipes from a head of water, considerably raised above the orifices from which the water is required to be projected. The form and direction of these orifices determine the figure which the jet or fountain will assume; and the height of the water transmitting the pressure will determine the altitude to which the water of the fountain will be projected.

Fig. 35.



(48.) Instruments for *levelling* or determining the direction or position of horizontal lines, or the relation between the levels in which different objects are placed, are constructed by means of the property by which liquids maintain their level. Let A, *fig.* 35., be a straight glass tube, having two other glass tubes, B and C, united with it at right angles. Let the tube A, and a part of each leg B and C, be filled with a liquid, the legs B and C being presented upwards. On the surfaces *a b* of the liquid in the legs, let floats be placed, carrying upright wires, to the ends of which are attached sights, S T, con-

sisting of two fine threads or hairs stretched at right angles across a square: these sights are placed at right angles to the length of the instrument, and a front view of them is represented at S T; and they should be so adjusted that the points where the hairs intersect shall be at equal heights above the floats. This adjustment may be made in the following manner: —

Let the eye be placed behind one of the sights, looking through it at the other, so as to make the points where the hairs intersect cover each other, and let some distant object covered by this point be observed. Let the instrument be now reversed, and let the points of intersection of the hairs be viewed in the same way, so as to cover each other. If they are observed to cover the same distant point as before, they will be equal heights above the surfaces of the liquid. But if the same distant point be not observed in the direction of these points, then one or the other of the sights must be raised or lowered, by an adjustment provided for that purpose, until the points of intersection be brought into that direction. These points will then be properly adjusted, and the line passing through them will be truly horizontal. All points seen in the direction of the sights will then be in the level of the instrument.

The principles on which this adjustment depends are easily explained: if the intersection of the hairs be at the same distance from the floats, the line joining those intersections will evidently be parallel to the lines joining the surfaces *a b* of the liquid, and will, therefore, be level. But if one of these points be more distant from the floats than the other, the line joining the intersections will point upwards if viewed from the lower sight, and downwards if viewed from the higher one. On reversing the instrument this line must take a different direction, and therefore will not be presented to the same object.

The accuracy of the results given by this instrument may be increased to any extent, by lengthening the tube A.

(49.) Another instrument for levelling is known by the name of the *spirit level*: it consists of a cylindrical glass tube filled with spirits of wine, except a small space which is occupied by air; the ends are hermetically sealed, to prevent the escape of the fluid. In whatever position the tube be placed, the liquid will always tend to the lowest part of it; if either end be raised above the other, at that extremity will the bubble of air be found, the liquid having retired to the other. If the extremities be at the same level, the bubble of air will settle at the highest intermediate point. The tube is not strictly straight, but is slightly curved, the convexity being presented upwards. Whatever be the position of the tube the air bubble will rest at the highest point of the curve; and if the extremities be at the same height, this will be the middle point. The tube in a horizontal position, with the air bubble resting in the centre, is represented in *fig.* 36.

Fig. 36.

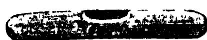
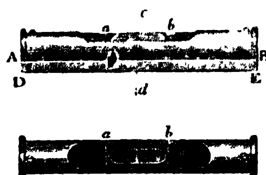


Fig. 37.



The method of mounting the level for the purpose of fixing a plane in a horizontal position, is commonly to fix the tube in a block of wood, or in a case of brass, A B, *fig.* 37. The block is fixed in such a position, that when the lower surface, D E, is horizontal, the bubble will stand in the centre between two lines, *a* and *b*, cut upon the tube. The instrument may be adjusted by the following method: — Let a plane surface be con-

structed as nearly horizontal as possible, and let the surface D E be placed upon it. Let the tube be fixed into the block in such a manner that the bubble will stand between the wires *a* and *b*; this being accomplished, let the instrument be now reversed, the extremities D and E exchanging places. If the bubble stand still in the middle, it proves the instrument to be correct; if not, the end towards which it retires is the higher extremity. The bubble must then be brought back to the centre, partly by lowering the extremity of the tube toward which it moves, and partly by adjusting the plane surface on which the instrument is placed. The instrument must now be once more reversed, and the same process repeated, until the change of position of the instrument no longer deranges the position of the bubble.

The principle on which this adjustment depends, is that the bubble will fix itself at the highest point of the tube, and that a horizontal line is at right angles to a vertical one. When by adjusting the tube the bubble is fixed in the centre of the wires *a* and *b*, let us suppose a vertical line, *c d*, drawn from the centre of the bubble to meet the base, D E, of the instrument. If D E be perpendicular to *c d*, it is apparent that reversing the instrument will make no change in the position of the line *c d*, and that the point *c* will still continue to be the place of the bubble. But in this case D E being perpendicular to a vertical line must be horizontal. If, however, D E be not perpendicular to *c d*, one of the angles, suppose *c d* D, will be acute, and the other, *c d* E, obtuse; and, therefore, the point D will be more elevated than the point E. On reversing the instrument, E will take the more elevated, and D the less elevated position. The middle point, *c*, will no longer be the highest point of the tube, and accordingly the bubble will retire from it.

CHAP. V.

OF THE IMMERSION OF SOLIDS IN LIQUIDS.

TO DETERMINE THE EXACT MAGNITUDE OF AN IRREGULAR SOLID. — WHEN SOLUBLE IN THE LIQUID. — WHEN POROUS. — EFFECT ON THE APPARENT WEIGHT OF THE LIQUID. — EFFECT ON THE APPARENT WEIGHT OF THE SOLID. — THE REAL WEIGHT OF THE SOLID AND LIQUID NOT CHANGED BY IMMERSION. — CAUSE OF THE APPARENT CHANGE. — WHEN A BODY IS SUSPENDED. — FLOATING BODIES. — THESE PROPERTIES DEDUCED FROM THE FUNDAMENTAL PRINCIPLES OF HYDROSTATICS. — THE SAME SOLID SINKS IN SOME LIQUIDS AND RISES IN OTHERS. — BUOYANCY. — ITS EFFECTS IN SUBMARINE OPERATIONS. — ITS EFFECTS PERCEIVABLE IN BATHING. — BOATS MAY BE FORMED OF ANY MATERIAL, HOWEVER HEAVY. — AN IRON BOAT, WHICH CANNOT SINK. — METHOD OF PREVENTING SHIPS FROM FOUNDERING. — EFFECTS OF THE CARGO. — BALL COCK, AND OTHER FLOATING REGULATORS. — MEANS OF RAISING WEIGHTS FROM THE BOTTOM OF THE SEA. — METHOD OF LIFTING VESSELS OVER SHOALS. — LIFE-PRESERVERS. — SWIMMING. — WATER FOWL. — FISH. — WHY A DROWNED BODY FLOATS. — PHILOSOPHICAL TOY. — WHY ICE FLOATS. — ROCKS RAISED TO THE SURFACE BY ICE.

(50.) To ascertain by direct measurement the volume or size of a solid body is a problem of considerable practical difficulty, except in cases where the body has some regular shape or figure; thus, for example, if it were required to determine the exact number of solid inches and parts of a solid inch in a rough lump of mineral ore, the surfaces of which present numerous and irregular projections and cavities, science would in vain furnish rules for calculating the volume of bodies bounded by surfaces of given figures and magnitudes, and meeting under given angles. The exact practical solution of the problem by direct geometrical measurement is impossible.

Bodies in the liquid form do not present the same difficulties; their peculiar qualities cause them to adapt themselves with facility to any form, and, without under-

going any change of magnitude, to take the figure of any vessel in which they are placed. Thus, if it be required to ascertain the number of cubic inches in a mass of liquid, let a perpendicular vessel be taken, the base of which is equal to a cubic inch, and let the liquid be poured into this vessel ; so much of the liquid as fills a part of this vessel one inch in height has the magnitude of one cubic inch ; so much as fills it to the height of an inch and a half has the magnitude of a cubic inch and a half ; and so on for other heights.

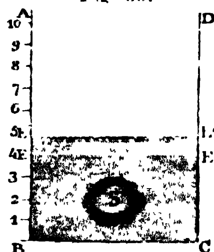
This great facility which the measurement of liquids presents, and the difficulty, on the other hand, which attends the measurement of solids, are the causes why the quantity of bodies in the liquid form is usually expressed by their measure, while the quantity in the solid form is commonly expressed by their weight: thus, if we speak of a liquid, we say it is so many hogsheads, gallons, quarts, &c.; on the other hand, speaking of a solid, we say it is so many tons, hundreds, pounds, &c.

(51.) The same property which renders the volume of a liquid easily determined, also points it out as the means of determining the dimensions of a solid. As a liquid will adapt itself to the shape of the vessel which contains it, filling every part of that vessel below its own level, it will in like manner adapt itself to the figure of any solid which may be immersed in it ; so that if the liquid were hardened and solidified, and the solid withdrawn, an exact mould of the solid would be exhibited by the hardened liquid. Such, in fact, is the method by which all moulds are made. A body naturally solid is liquefied by exposure to heat, or by moisture, or by other means. The solid, the shape of which is to be taken, is then immersed in it, and the liquid is hardened either by cooling, or drying, or otherwise. The body is then withdrawn, leaving its form impressed on the substance in which it was immersed.

When a solid is thus immersed in a liquid, it displaces a quantity of that liquid equal to the dimensions of that part of the solid which is immersed. If, there-

fore, the dimensions of the liquid thus displaced could be ascertained, the magnitude of the part of the body immersed would be determined.

Fig. 38.



This is easily accomplished. Let A B C D, *fig.* 38., be a vessel containing a liquid, which we will suppose, in the first instance, stands at a level, E F; we shall suppose also, for the present, that the vessel has perpendicular sides: let a solid, S, whose dimensions are to be ascertained, be now plunged in the liquid. The space which the solid occupies below the surface of the liquid having been previously filled with liquid, the liquid which so filled it, being now excluded, must find room elsewhere. By yielding its place to the solid, it will itself displace the adjacent particles of liquid, and a general change of position will take place in the whole mass. The surface E F will rise to the level E′ F′. The space between E F and E′ F′ must evidently be equal to the dimensions of the solid S, because it is the increased space which the liquid occupies, owing to the exclusion of part of it from the space now occupied by the solid. In fact, we may consider that portion of the liquid which previously occupied the space S to be removed to the space between the levels E F and E′ F′. Thus, by means at once simple and easy, we have obtained a body E F F′ E′, of a regular shape and easily measured, which we are infallibly certain is equal in magnitude to the irregular solid S, the dimensions of which we would in vain attempt to determine by the

nicest instrumental measurement, guided by the strictest mathematical rules.

If we conceive the vessel A B C D to be of glass, and divisions marked on its exterior surface by parallel lines from the bottom to the top, as represented in the figure, the interval between each division may correspond to any given magnitude, as a cubic inch of liquid. The whole quantity of liquid in such a vessel will be expressed by the number which marks the division, and the fraction of a division, at which its surface stands. Thus, if the level of the liquid in the vessel stand at one third of the division above that marked 5, the total quantity of liquid in the vessel will be 5⅓ cubic inches. Let us suppose liquid be poured in until the surface rises to the sixth division: let it be now required to determine the magnitude of an irregular lump of ore. Plunge it in the liquid, in which it will sink by its superior weight, and observe the division to which the surface has risen. Suppose this to be one fourth of a division above the eighth. It appears, then, that the piece of ore has displaced as much liquid as would raise the level two and a quarter divisions; and, therefore, its magnitude is two and a quarter cubic inches.

We have here supposed that we possess a vessel previously graduated, so that each division shall correspond to a given quantity of liquid. The same property which suggests the use of such a vessel also suggests the method of graduating it. Let a solid be formed into the exact shape and size of a cubic inch, and some liquid having been poured into the vessel sufficient for the total immersion of the solid, let a line be drawn on the vessel, marking the place of its surface; the solid being then immersed, let another line be drawn, marking the place to which the surface of the liquid has risen. The interval between these two lines will then be a division which corresponds to a cubic inch of the liquid. If the sides of the vessel be truly perpendicular, and its inner surface subject to no inequalities, nothing more will now be necessary than to draw a line upon the vessel from top

to bottom, and to divide it into parts equal to the space we have just obtained; each division will then correspond to a cubic inch of the liquid: the divisions may evidently be subdivided into fractional parts to any extent that may be required.

If, however, the sides of the vessel be not perpendicular, or being so, if, as will inevitably happen, they be subject to inequalities more or less in amount according to the accuracy with which the vessel is made, then the method of division which we have just adopted will not give true results. It is only where the sides of the vessel are uniform from top to bottom, that equal divisions will correspond to equal quantities of the liquid. If one part be wider or narrower than another, an equal length of that part will contain more or less liquid than the other; and as our object is to divide into equal parts the liquid, and not the height of the vessel, it will follow that the degrees must be smaller where the vessel is wider, and *vice versâ*. Besides the inequalities incident to vessels intended to be straight, it does not always happen that such a vessel is convenient for use. The graduated vessels used by apothecaries and others, who have occasion for exact liquid measures, are more frequently of the tapering form of a wine-glass; the divisions on the sides of such vessels will be wider near the bottom, and narrower near the top. Such a vessel may be graduated by repeatedly plunging into it the same solid, and marking the changes of level which it produces, filling the vessel with liquid to the new division each time the solid is withdrawn: or it may be effected by continually pouring into it a previously ascertained measure of liquid, and marking the successive changes of level.

The effects of immersion not only measure the total dimensions of a solid, but also determine any required part of it. If the solid be only partially immersed, that part which is below the surface of the liquid, displacing a portion of the liquid equal to its own bulk, will cause the surface of the liquid to rise, and the space through

which it rises will indicate the magnitude of the part of the solid which is immersed.

A solid body may thus be easily divided into two or more parts having any given proportion to each other. Suppose it be required to divide a solid into two equal parts. Let the solid be totally immersed in a liquid, and observe the height to which the surface of the liquid rises. Let the solid be now withdrawn from the liquid, and let it again be partially immersed until the surface rise through half the former space; the liquid displaced will then be half the quantity which was displaced by the total immersion of the solid: therefore the part now immersed must be half the magnitude of the whole. If a line be marked on the solid at the points where the surface of the water meets it, a division made through this line will divide the solid into two equal parts. In the same manner, if it were required to cut off a fifth part of the entire magnitude, it will be only necessary to immerse it, until the surface of the water rise in the vessel, through a space equal to the fifth part of the space through which it would be raised by the total immersion. It is evident that a similar process would enable us to cut off any required part of the body; and a repetition of the process applied to the remainder of the body would enable us to cut it into any number of parts, equal or unequal, or bearing any required proportion to each other.

There are circumstances which occasionally impede the practical use of the method of measuring a solid by immersion. Thus, for example, if the solid be soluble in the liquid, the method fails. In this case, however, some other liquid may generally be selected, in which the solid is not soluble. Again, if the body be of such an open or porous texture as to allow the liquid to penetrate its dimensions, the method evidently fails, because the solid does not displace a quantity of the liquid equal to its magnitude. The liquid which enters the pores still occupies its former place; and the portion displaced is, in fact, only the difference between a quan-

tity of liquid equal in bulk to the body, and the quantity which the body absorbs. If the absorption of the liquid do not affect the dimensions of the solid, the method may still be applied by saturating the solid previously to the experiment being tried.

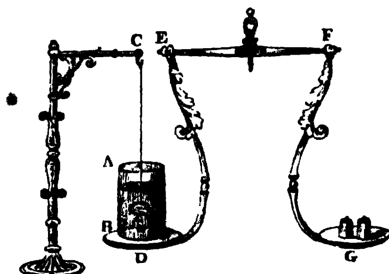
From what has been stated it follows, that if a solid be plunged into a vessel filled with a liquid, as much of the liquid will overflow as is equal to the magnitude of the solid immersed. And a vessel which is only partially filled, will become brimful by the immersion of a solid, whose magnitude is equal to the part unfilled. Thus a teacup, which is filled to the brim with tea, will overflow when sugar is put in; and a bath should never be filled beyond such a height as will allow an unfilled space equal to the aggregate magnitude of the bodies of the bathers.

(52.) We have seen the effect which the immersion of a solid produces upon the volume of a liquid. This effect is sometimes expressed by stating that the volume of the liquid receives an increase equal to the volume of the solid; by this, however, it is not meant that the absolute dimensions or measure of the liquid are increased, but merely that the apparent dimensions included within the external boundaries of the liquid are augmented by the magnitude of the solid. In fact, the contents of the vessel in this case are the liquid and the solid together; but the solid being surrounded with the liquid, the dimensions of the liquid are estimated by its exterior surfaces, in the same manner as the dimensions of a rock would be estimated by its external limits, even though it should contain within it a cavity filled by any other substance.

We shall now consider what effect is produced upon the apparent weight of a liquid by the immersion of a solid. Let A B, *fig.* 39., be a vessel containing a liquid, placed in the dish D of a balance E F, and counterpoised by weights in the opposite dish G. The weights in G will then be equal to the weight of the vessel A B, and the weight of the liquid it contains. Let a solid, S, heavy enough to sink in the liquid, be now suspended by a

horse hair, or fine thread, from an arm C, and let the arm C be so placed as to allow the solid S to sink into the liquid until it is totally immersed, but so that it shall not touch the bottom of the vessel. It will be observed that the dish D will immediately preponderate,

Fig. 39.

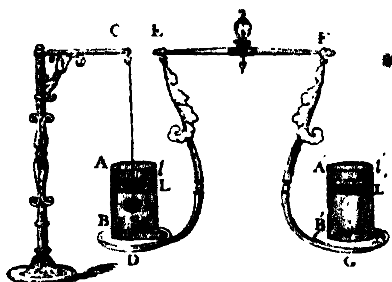


the weights in G being no longer sufficient to counterpoise the weight in the opposite dish D. Hence we infer at once, that as the apparent dimensions of the liquid were increased by the immersion of the solid, so also is the apparent weight of the liquid augmented. But the amount of this increment of weight is still to be found.

Let additional weights be placed in the dish G until equilibrium be restored: the amount of these weights will express the increase which the apparent weight of the liquid receives from the immersion of the solid. Let these additional weights be now removed, and let the solid S be also removed from the vessel A B. The balance will then again be an equilibrium. The height to which the surface of the liquid in the vessel A B was raised by the immersion of the solid S having been observed, let so much more liquid be poured into the vessel A B as will raise the surface to that point. This quantity, according to what has already been explained, is equal in bulk to the solid S; and by the weight of this quantity the dish D will now preponderate. Let the weights which restored the equilibrium when the solid

was formerly immersed be now again placed in the dish G, and equilibrium will be once more restored. It therefore follows, that the increase which the apparent weight of the liquid receives from the immersion of a solid is equal to the weight of the portion of liquid which the solid displaces.

Fig. 40.



As this is a principle of the highest importance in the theory of fluids, and indeed in physical science generally, it may not be useless here to present its experimental illustration under another point of view. Let A B and A' B', *fig.* 40., be two similar and equal glass vessels of equal weight, and let them be filled to the same level L and L', with water, and placed in the dishes of a balance. Being of equal weight, they will then be in equilibrium. Let a solid S, suspended as in the former case, be immersed in A B. The dish D will preponderate; and the level L will rise to *l*. Let water be now poured in A' B', until the equilibrium be restored. It will be found that the level of the water in A' B' has been raised through the same space by the additional water necessary to restore the equilibrium, as the level of the water in A B has been raised by the immersion of the solid. The conclusion is evident. The immersion of the solid gives to the vessel an increase of weight equal to that which it would receive from the addition of so much water as the solid displaces.

(53.) We have here supposed the immersion of the solid to be total; and, consequently, the weight imparted to the liquid is that of a portion of the liquid itself equal to the whole bulk of the solid. But the same experiments will give similar results, if the solid be only partially immersed. Still the weight which the liquid will receive, will be equal to the weight of that portion of it which will be displaced by the part of the solid immersed. It will not be necessary here to repeat the experimental process by which this is verified; it is the same, in all respects, as has been already explained with reference to total immersion.

The manner in which the immersion of the solid has been described in the preceding experiments, by suspending it from the arm C by a thread or hair, requires that the solid should be one which, by its weight alone, will sink in the liquid. The conclusions at which we have arrived are not, however, limited to such bodies. If, therefore, the solid to be immersed be one so light that it would float on the liquid, its immersion must be produced by a different means; it must be pressed into the liquid by a rigid inflexible wire, or some other means. When this is accomplished, however, all the results are conformable to what has been already explained.

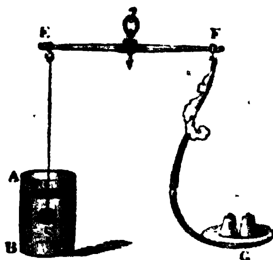
From all which has been stated, we may, therefore, infer that the immersion of any solid, whether total or partial, increases both the apparent bulk and the apparent weight of the liquid; and that it increases both exactly in that degree in which they would be increased by the addition of so much of the same liquid as is equal in magnitude to the immersed solid.

(54.) The weight both of the liquid and the solid immersed in it, depends on the attraction which the earth exerts on their particles; and, therefore, so long as the mass of the liquid and the mass of the solid remain unaltered, their weights in the same place must be immutable. It follows, therefore, that the increase of weight which the vessel receives from the immersion of the

solid cannot proceed from any increase of weight in either the vessel or the liquid, nor can it proceed from any increase or diminution in the weight of the solid immersed; the mere fact of immersion can cause no change in the amount of these weights.

It is natural, therefore, to enquire whence the increase of weight which the vessel receives by the immersion of the solid proceeds. We have seen that the actual weight of the water contained in the vessel remains unaltered, while its apparent weight is increased. We know that the actual weight of the solid cannot be altered; but it is still to be seen how its apparent weight is affected. Let us suppose the solid immersed to be heavier than water, and let it be suspended from the arm of a balance, as represented in *fig.* 41.. and counterpoised. Let it then

Fig. 41.



be immersed in the liquid contained in the vessel, as represented in the figure. Immediately the equilibrium will be destroyed; the dish G will preponderate, and the arm E will rise: it therefore appears that by immersion the apparent weight of the solid is diminished. Let us now enquire the amount of this diminution. Remove from the dish G such a quantity of weight as will restore the equilibrium, so that the dish G will no longer preponderate, but will exactly counterpoise the weight suspended from E. The weight thus removed is the amount by which the apparent weight of the solid is diminished by immersion. Let the quantity of the

liquid be obtained by means of a balance, the weight of which is equal to the weight removed from the dish G. Let the level at which the liquid stands in the vessel A B be marked on its side, and let the solid be then removed from it; the surface of the liquid will immediately fall, leaving a space between its former and present level equal to the magnitude of the solid. Let the liquid, whose weight was ascertained to be that which was lost by the apparent weight of the solid, be now poured into the vessel A B, the surface will rise to the point at which it stood when the solid was immersed.

Hence it must be evident,

1. That by the process of immersion, while the apparent weight of the liquid is increased, the apparent weight of the solid is diminished.

2. That the increase which the apparent weight of the liquid receives is exactly equal to the diminution of the apparent weight of the solid: and,

3. That the amount of this increment of the one apparent weight, and decrement of the other, is the weight of a portion of the liquid whose magnitude is equal to the magnitude of the solid.

If we pursue these conclusions into their consequences, we shall obtain some remarkable results. Suppose it should so happen, that the body selected for immersion is one whose weight is equal to the weight of its own bulk of the liquid; by the principles just established it will lose by immersion its whole weight; and, consequently, when immersed, if it were suspended from the arm of a balance, it would weigh nothing; that is, the thread which connects it with the arm would be stretched by no force, and the body would have no tendency to descend: and, accordingly, we find this to be actually the case. Let a hollow brass ball be provided, with a means of enclosing fine sand within it; by this means let the weight of the ball be so adjusted as to be equal to that of its own bulk of water, and let it be thrown into a vessel of that liquid. It will be found that it will remain suspended indifferently in any position, provided

it be totally immersed. If it be placed at the bottom, there it will remain; if it be placed any where between the surface and the bottom, it will also remain suspended there; if it be placed at the surface, but so that no part shall be above it, there it will also remain.

There is another remarkable consequence obviously collected from what has been proved. If the solid immersed in a liquid have less weight than its own bulk of the liquid, it would follow, by total immersion, it loses *more* than its own weight; a consequence not as absurd as it may at first seem to be. When a body, by immersion, loses less than its whole weight, it has a tendency to descend with what remains. When a body loses exactly its whole weight, the effect of its gravity is neutralised, and it loses all tendency to move, as in the example just produced. But when the consequences would justify us in affirming that it loses more than its entire weight, the effect is manifested not merely by the body losing all tendency to sink, not merely by lying passively in the liquid, but by exhibiting a positive tendency to rise; by acquiring, in fact, a quality the very reverse of weight. Those who have been used to the signification of negative signs in algebra will perceive the tendency of this reasoning, and will find in it the illustration of the true meaning of such symbols. For those who are not conversant with the elements of mathematics, it is hoped that enough has been said to elucidate the utility of extending the application of a theorem, by giving a greater latitude to the signification of the terms in which it is expressed.

The phenomena of floating bodies are verifications of the inference which has just been made. Let the hollow brass ball, already alluded to, be so loaded that it shall be lighter by any proposed weight than its own bulk of water; let it then be immersed in a vessel of that liquid, and placed below the surface. It will be found that the ball will not remain there, but will ascend to the surface, on which it will float. To keep it below the water a certain force will be necessary; and if this

force be measured, it will be found to be equal to the excess of the weight of a portion of liquid equal in bulk to the ball above the weight of the ball.

The conclusions to which we have arrived may, therefore, be generalised as follows :—

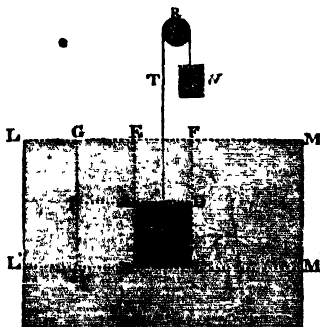
1. A solid whose weight exceeds the weight of its own bulk of a liquid has a tendency equal to such excess to sink when immersed in the liquid.

2. A solid whose weight is equal to the weight of its own bulk of liquid, when immersed in the liquid, has no tendency to sink or rise.

3. A solid whose weight is less than the weight of its own bulk of a liquid has a tendency to rise when immersed in that liquid; which tendency amounts to the excess of the weight of a portion of the liquid equal in bulk to the solid above the weight of the solid.

(55.) The reasoning by which we have arrived at these conclusions has been founded on the results of the experiments described in (52.). They may, however, be inferred from the fundamental principle of HYDROSTATICS; viz. that fluids transmit pressure equally in all directions.

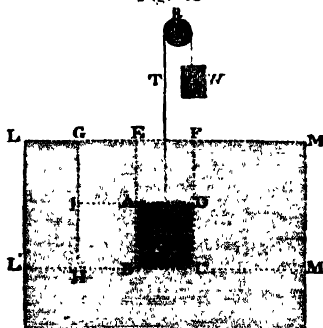
Fig. 42.



Let us suppose a solid, A B C D, *fig.* 42., of any proposed figure, as that of a cubic inch, immersed in a liquid, the surface of which is L M, and let L′ M′ be the

level on which the bottom B C is placed. Let the solid be suspended by a fine thread T, the weight of which may be neglected; and let this thread be carried over a grooved wheel R, such a weight W being appended to it as will counterpoise the solid A B C D, and keep it

Fig. 42.



suspended in the liquid without either rising or sinking. In this state every part of the level L' M' must sustain the same pressure downward; for, if any one part suffered a greater pressure than another, the liquid below the level L' M' would transmit the greater pressure undiminished in the upward direction to the point where the lesser pressure is supposed to act; and this point would move upwards, by reason of the excess of the upward pressure; but no such effect is supposed to take place, and therefore no part of the level L' M' is under a greater pressure than another.

The bottom B C of the solid occupies a square inch of the level L'M'. Let the column resting on BC, of which the solid forms a part, be imagined to be continued to the surface. It is evident that the downward pressure excited on the base B C will be equal to the weight of the incumbent column E B C F diminished by the weight of the counterpoise W. This column consists partly of the liquid E A D F, which is above the solid, and partly of the solid itself. Since this down-

ward pressure is sustained by the stratum L′M′ at B C, it follows that every part of that stratum equal in magnitude to B C must sustain the same downward pressure. Take H B, equal to B C, and the part H B sustains a pressure arising from the weight of the column of liquid G H B E, which rests upon it. The weight of this column must, therefore, be equal to the weight which presses on B C.

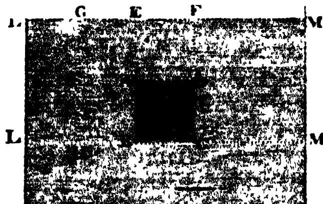
Let us suppose the column G H B E divided into two at I A; so that the part I A B H shall be equal in bulk to the solid A B C D, and the part I A E G equal to the liquid E A D F above the solid. Let us now compare the equal pressures which act on B C and B H. The former is the weight of E A D F, together with the weight of the solid diminished by the weight of the counterpoise W. The latter is the weight of G I A E, together with the weight of I A B H. It appears, therefore, that the weight of the column E B C F exceeds that of the column G H B E by the weight W. But since the part E A D F of the first column is equal in weight to the part G I A E of the second, it follows that the weight of the solid A B C D exceeds the weight of its own bulk I A B H of the liquid by the weight of the counterpoise W.

Now, since the counterpoise W is the force which prevents the solid from sinking, it expresses the tendency of the solid to sink, and it therefore follows, that this tendency is estimated by the excess of the weight of the solid above the weight of its own bulk of the liquid, according to what has already been experimentally established.

In the preceding reasoning, the solid has been supposed to exhibit a tendency to sink when immersed in the fluid, which tendency has been checked by the counterpoise. Let us now consider the case of a solid which remains suspended in the liquid without any tendency to sink or rise. In this case the pressure on B C, *fig.* 43., is the weight of the solid, together with that of the fluid above it; while the pressure on H B is equal to the

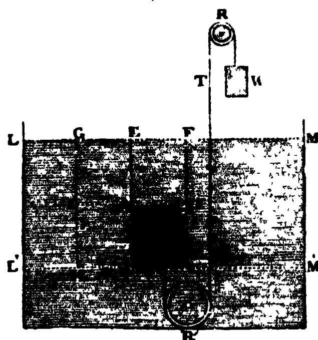
weight of the liquid I A B H, equal in bulk to the solid, together with the weight of the liquid G I A E equal to the liquid above the solid; since the pressure on H B and B C must be equal, the weights of the columns

Fig. 43.



G H B E and E B C F are equal. From these equals take away the weights of the liquid G I A E and E A D F respectively, and the remainders, which are the weights of the solid and its own bulk of liquid, will be equal. Thus, in conformity with the results of experiment, it appears that a solid which remains suspended in a liquid must be equal to the weight of the liquid which it displaces.

Fig. 44.



Finally, let us consider the case in which the solid immersed has a tendency to rise to the surface; suppose a fine thread attached to the bottom of the solid to be carried under a grooved wheel R′, *fig.* 44., and, being

brought upwards, to be passed over another grooved wheel R, and let such a weight W, be appended to it as will check the tendency of the solid to rise to the surface, but not sufficient to cause it to sink. The solid A B C D therefore remains suspended in the liquid.

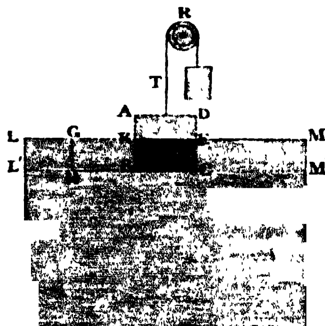
According to the reasoning used in the former cases, it may be inferred that the pressure on B C must be equal to the pressure on B H. The pressure on B C is equal to the weight of the solid, the liquid above it, and the counterpoise W. The pressure on B H is equal to the weight of the liquid I A B H, equal in bulk to the solid, together with the weight of G E A I, equal to the weight of the liquid above the solid. From these equals take away G E A I and E F D A, and the remainders will be equal; that is, the liquid, equal in bulk to the solid, will be equal to the weight of the solid, together with the counterpoise W. It therefore appears, that a portion of the liquid equal in bulk to the solid exceeds the weight of the solid, by that weight which is just sufficient to prevent the solid ascending to the surface and to keep it suspended in the liquid. Hence, in conformity with what has already been experimentally proved, it appears that a solid lighter than its own bulk of the liquid has a tendency, when immersed in the liquid, to rise to the surface with a force equal to the difference between its weight and that of its own bulk of the liquid.

The fact that a solid equal in weight to its own bulk of liquid will remain suspended indifferently in any position in the liquid, may also be very easily comprehended, by considering that the liquid itself remains quiescent. If, then, we take any portion of the liquid beneath its surface, say a cubic inch at the depth of one foot, that cubic inch of liquid remains at rest. Suppose it now to be congealed and to become solid, — not, however, altering in any way its bulk,—it will evidently still remain at rest, because the fact of it becoming solid introduces no force to put it into motion. It will, therefore, be in the case of any solid immersed in the liquid equal in weight to the liquid which it displaces.

But it will be more philosophical to deduce the fact of the suspension of the solid from the reasoning already given, and founded on the distinctive property by which a fluid transmits pressure; and this same property is that on which the quiescence of all parts of a liquid depends.

(56.) We have hitherto considered the cases only in which the solid is totally immersed. The effects of partial immersion are in all respects similar, and investigated on the same principles.

Fig. 45.

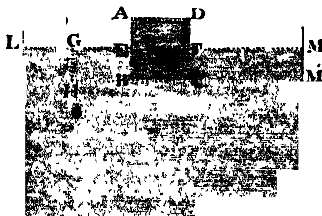


Let A B C D, *fig.* 45., be a solid partially immersed in a liquid whose surface is L M, and having a tendency to sink still deeper, which tendency is checked by the counterpoise W. Since the solid is in equilibrium, the stratum L′ M′ of the liquid, immediately below its base, must be equally pressed in every part. The pressure on B C is equal to the weight of the solid diminished by the counterpoise W. Let H B be a portion of the stratum equal to B C; the pressure here, which is equal to the former, is the weight of the column G H B E. This column is evidently equal to the weight of the liquid displaced by the solid; and therefore it follows, that the weight of the liquid displaced by the solid is equal to the weight of the solid diminished by that of the

counterpoise; or, what amounts to the same, the weight of the counterpoise is equal to the excess of the solid above that of the liquid which it displaces. Thus the same property belongs to the partial immersion of the solid, as has been already proved to appertain to total immersion.

This result may be verified experimentally, by attaching the thread which supports the solid A B C D to the arm of a balance, and ascertaining the weight from the opposite arm which will support it. This being done, and the level of the surface L M being observed, let the solid be removed from the liquid; the counterpoise from the opposite arm will no longer be able to sustain the solid. Let such an additional weight be added as will support it, and take a quantity of the liquid, the weight of which is equal to this additional weight. This quantity, being poured into the vessel, will restore the level L M to its former height: hence it appears that this quantity is equal in magnitude to the part of the solid which was immersed.

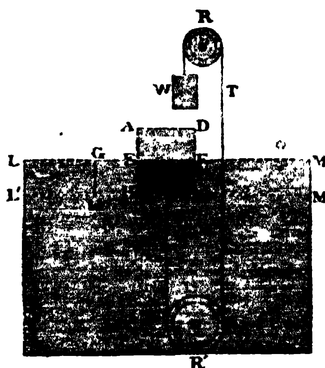
Fig. 46.



If the solid partially immersed have no tendency either to sink or rise, the counterpoise W will be unnecessary. In this case the pressure on B C, *fig.* 46., is equal to the weight of the solid; and the equal pressure on H B is equal to the weight of the liquid displaced by the solid. Hence it follows, that when a solid floats on a liquid, it displaces as much liquid as is equal to its own weight.

This may be verified experimentally. Let a solid which floats on a liquid be first weighed, and let a portion of the liquid of equal weight be ascertained. Let the level of the liquid in a vessel be observed, and let the change of this level be ascertained, which is produced by the solid floating on its surface. It will be found that the same change of level will be produced by pouring into the vessel as much liquid as is equal to the weight of the solid. If it be remembered that the change of level is owing to the space beneath the surface of the liquid occupied by the solid, it will be easily understood that the portion of liquid displaced by the solid is that which is necessary to produce the same change of level, and this portion is equal in weight to the solid.

Fig. 47.



It may happen that a solid partially immersed has a tendency to rise. Let this tendency be checked by the force of the weight W, *fig.* 47., drawing the solid downwards. The pressure on B C is here equal to the weight of the solid, together with the weight W; and this, as before, is equal to the weight of G E B H, the liquid displaced by the solid. Hence it appears that W, which expresses the tendency of the solid to rise, is equal to

the excess of the weight of the fluid displaced by the solid above the weight of the solid.

This, also, may be verified experimentally, by removing the weight W, and connecting the string with the arm of a balance. It will be found that the counterpoising weight, together with the weight of the solid, is equal to the weight of as much liquid as would produce the same change of level as is produced by the partial immersion of the solid.

The consequences which have been just inferred are so important that it may be useful here to recapitulate them.

Whenever a solid is immersed in a liquid, whether the immersion be partial or total, it will have a tendency to sink, if its weight be greater than the weight of the liquid which it displaces.

It will have a tendency to rise if the weight be less than that of the liquid which it displaces.

It will have no tendency either to rise or sink if its weight be equal to that of the liquid which it displaces.

No solid can float on the surface of a liquid if it be heavier than its own bulk of the liquid; because, in order to float it is necessary that the liquid displaced be equal in weight to the solid, which it cannot be, if the weight of the solid be greater than that of its own bulk of the liquid.

In whatever position a body floats, it will always displace the same quantity of liquid, because it will always displace a portion of liquid equal to its own weight.

The effect, therefore, of immersion in every case is to lessen the apparent weight of the solid immersed by affording support to its real weight.

(57.) The support, whether partial or total, which a solid thus receives from a liquid, is an effect with which every one is familiar, and which is commonly expressed by the term buoyancy. From the results which have been just established, it appears that a solid is buoyant in a liquid, in proportion as it is light and as the liquid is heavy. Thus the same solid will be more buoyant in

quicksilver than in water; and in the same liquid cork is more buoyant than lead. Again, a solid which has buoyancy enough to float in one liquid will sink in another. Thus glass will sink in water but will float in quicksilver. A block of lignum vitæ, or a piece of ebony, will sink in alcohol but will float in mercury. A block of ash or beech will float in water but will sink in sulphuric ether. The reason is, that the weight of glass is greater, bulk for bulk, than that of water, and is less than that of mercury. The weight of lignum vitæ, or ebony, is greater, bulk for bulk, than that of alcohol, but less than that of water; and the weight of ash or beech is less, bulk for bulk, than that of water, but greater than that of sulphuric ether.

If a rope be attached to a heavy block of stone at the bottom of a reservoir of water, it may be raised to the surface by the strength of a man; but as soon as any quantity of it emerges from the surface, the same strength will be insufficient to support it; it loses the support of the water, and requires for its support as much more force as is equal to the weight of the water which it has displaced. In building piers and other subaqueous works, this effect is rendered peculiarly manifest; the labourer feels himself endued with prodigiously increased strength, raising with ease, and adjusting in their places blocks of stone, which he would in vain attempt to move above the water. Such operations are carried on by the aid of a diving bell, a contrivance which will be explained in a succeeding part of this volume. After a man has worked for any considerable time in this way under water, he finds, upon removing to the air, that he is apparently weak and feeble: every thing which he attempts to lift seems to have unusual weight; and to move even his own limbs is attended with some inconvenience.

(58.) Every one who, while bathing, has walked in the water, is sensible how small a weight rests upon the feet. If the depth be so great that the body is immersed to the shoulders, the feet are scarcely sensible of any pressure on the bottom. The want of sufficient pressure in this case renders the body easily upset. In attempting

to ford a river in which there is a current, considerable danger is produced by this cause; even though the river should be sufficiently shallow to leave a large portion of the body above the surface. The pressure on the bottom being diminished by the buoyancy of the liquid, the feet have a less secure hold on the ground, and the force of the current acting on that part of the body which is immersed, without affecting that part which is above the surface, has a tendency to carry away the support of the feet.

A body composed of any material however heavy may be so formed as to float upon any liquid, however light. To effect this it is only necessary to give it such a shape as will cause it to displace a quantity of liquid, which is as many times greater than its absolute bulk, as its weight is greater than that of an equal bulk of the liquid. There are an infinite variety of figures which will accomplish this. A basin formed of porcelain, brass, or any heavier material, will float upon water if it be placed with its convex side towards the liquid. The water being excluded from the interior of the basin, as much liquid will be displaced as would be equal to the bulk of that part of the basin which is immersed, if, instead of being hollow, it were filled to the level of the liquid in the vessel. But if the basin be immersed with its concave side downwards, the water entering the hollow of the vessel, it can displace no more water than is equal to the actual bulk of material which composes the basin; and this material being heavier, bulk for bulk, than water, it will sink.

(59.) The method of adapting the shape of a body heavier, bulk for bulk, than a liquid, so as to cause it to float, depends on giving it such a shape as that, when immersed in the water, there will be, below the level of the liquid, some space in the vessel occupied by air or by some substance lighter than the liquid. Thus, if a teacup be placed with its bottom downwards on the surface of water contained in a basin, it will float; but if the depth to which it sinks be observed, it will be

found that a part of the hollow of the cup is below the surface of the water. In this case, therefore, the space below the level of the liquid is occupied partly by the porcelain of which the cup is composed, and partly by the portion of air which occupies that part of the hollow of the cup below the surface of the water. It is the lightness of this portion of air, compared with water, which enables the cup to float. That this is the case may be proved by the following experiment. Let water be poured into the cup thus floating, and observe the level of the water in the cup and in the vessel; the former will always be found below the latter; so that a stratum of air still lies below the level of water in the basin. And this will be the case until the cup be completely filled with water, when, no space being left for air below the surface, the cup will sink to the bottom.

For these reasons a ship or boat, composed of a material which is heavier, bulk for bulk, than water, will sink when filled with water by a leak or otherwise; but if the material be lighter she will continue to float, though at an increased depth: in such a case the ship is said to be water-logged. Many ships are made of a sort of timber, such as teak, which is heavier, bulk for bulk, than water. And, indeed, if the average weight of all the materials which enter into the construction of an ordinary vessel be taken, it is probable that they are heavier than their own bulk of water. Whether a vessel, however, will sink by being water-logged, will depend as much upon the nature of the cargo as the vessel itself. A vessel laden with iron, or with any other heavy substance, will, in such a case, sink; while one laden with cork, timber, or any other light substance, will float.

(60.) An iron boat will float with perfect security; and, if it be formed with double plates of metal, including between them a sufficient hollow space, and so united as to exclude the water, no circumstance can sink it; for, whatever be its position, it will displace more water than is equal to its own weight.

A contrivance to prevent ships foundering at sea,

founded on this principle, has lately been published by Mr. Ralph Watson. He proposes to carry through various parts in the hulk of the ship, so situate as not to interfere with the usual arrangements of freight or accommodation for passengers, metal tubes closed at both ends, so as to exclude water. In case of the ship foundering, by a leak or otherwise, the interior of these tubes will continue still unfilled with water; and, if their number and magnitude bear a sufficient proportion to the weight of the ship and cargo, the whole will float, even though there should be a free admission for the sea through the bottom of the vessel.

(61.) It is evident, from all which has been stated, that the degree of immersion of a vessel in the water is altogether independent of the nature of her freight, and will be the same as long as the weight of her cargo is the same, whether it consist of wool, leather, timber, or metal. Hence the weight of the cargo may be always estimated by the depth of immersion; and, if a graduated scale be marked upon the rudder of the vessel, the same scale will indicate the weight, whatever be the substances which compose the freight.

(62.) We have seen that a body lighter than a liquid will, when immersed, have a tendency to ascend to the surface: an inflated bladder, the weight of which is inconsiderable, will require as much force to keep it down as is nearly equal to the weight of the water which it displaces. If such a bladder be tied to a weight of several pounds at the bottom of a pond, its tendency to ascend will prevail over the weight, and it will draw it to the surface.

The buoyancy of solids immersed in liquids is frequently used as a means of regulating the supply of reservoirs, in which it is necessary to maintain the liquid at a certain level. If a solid body float on the surface, it will rise and fall with every change of level of the surface; and, if any impediment prevent its ascent or descent with the ascent or descent of the surface of the liquid, it will exert a force in the one case by its buoy-

ancy, and in the other by its weight, to overcome such impediment. The floating body is usually connected by a wire or lever, with a valve or cock which governs the supply of the liquid to the reservoir. When the vessel is filled to a certain height, the float being raised to that height acts by the wire or lever, so as to close the valve and stop the further supply of the liquid. If, on the other hand, by use or waste, the level of the liquid fall and the reservoir want replenishing, the float descends, and, acting on the valve in the contrary direction, opens it and admits the supply of liquid. Examples of this may be seen in the ordinary cisterns used for supplying water for domestic purposes. A leaden pipe is carried from the main pipe, and is introduced into the cistern which is to be supplied; at the extremity of this pipe in the cistern, is placed a stop-cock, which is worked by a lever, at the extremity of which there is a large hollow metal ball, which is raised by its buoyancy with the surface of the liquid, and falls by its weight when the surface descends. The cock is thus closed when the surface rises to a certain height, and stops the supply of water; but when the surface falls the cock is again opened, and water is admitted.

Many contrivances, upon this principle, have been suggested for raising sunken vessels. Hollow boxes made water-tight, and including only air, may be carried to the bottom by heavy weights attached to them. The boxes being secured to the vessel to be raised, the weights which sunk them may then be detached. If such a number of these boxes be attached to the vessel as will displace more water than is equal in weight to the vessel to be raised and the boxes themselves, the whole will float to the surface.

A machine upon the same principle, called the *camel*, for lifting vessels over shoals, is the invention of a burgomaster of Amsterdam named Bakker. In the Zuyder Zee, opposite the mouth of the river Y, there are two sand banks, between which there is a shallow passage, impassable to vessels of large size. It was the practice

for such vessels to take in their cargo after they had passed beyond this strait; but the accumulation of sand became at last so considerable, that some means were necessary to transport the vessels themselves over this obstacle. In 1672, large chests filled with water were fastened to the bottom of the vessel; the water was subsequently pumped out of these, so that they acquired a buoyancy or upward force equal to the weight of the water discharged: the ships were thus raised and enabled to pass the shallow. A similar contrivance had been previously used at Rome by a Dutch engineer named Meyer, but not so complete or effectual a one as that of Bakker.*

The camel, of which we have just explained the original idea, consists of two large hollow chests, so constructed as to extend along the sides of a vessel, and shaped on one side so as to lie close to her sides, being square upon the outside. Being filled with water they sink, and are without difficulty brought close to the sides of the vessel, to which they are attached by ropes which pass round each of them and under the keel; the water is then pumped out, and the buoyancy of the chests raise the ship in the water so as to enable it to float over a shoal. An East Indiaman that drew fifteen feet of water, was so much elevated by means of this machine that it only drew eleven feet; and the largest ships of war in the Dutch service, of from 90 to 100 guns, were always enabled to surmount the different sand banks of the Zuyder Zee. Such machines are likewise used in Venice and in Russia.

Life-preservers, provided in case of accident at sea, are constructed upon the same principle. A hose or flexible tube is composed of a cloth prepared by a solution of caoutchouc or India rubber, by which it becomes impervious to air or water, and which is also insoluble in water. It is made of such a length, that it may surround the waist and be secured by a buckle in front: a mouthpiece and valve are provided at one extremity of the tube, through which it may be inflated. When thus

* Brewster's Encyclopædia, v. 296.

filled with air it becomes light when compared with its own bulk of water; and, when surrounding the waist, it gives the body such buoyancy that the upper part of the person will continually be kept above the water.

The benefit of this contrivance in case of accidents at sea, and more especially when, as usually happens, they occur near the shore, might be rendered much more extensive. A long hose of water-proof cloth might be constructed, of such a magnitude as, when inflated, it would have sufficient buoyancy to sustain a considerable number of persons; straps might be attached to it at proper intervals, to be secured round the waists of those whom it was necessary to support. Such an apparatus, when not inflated, might be folded in a very small bulk; and a sufficient number of them to save the crew or passengers of any vessel would neither be expensive to construct or inconvenient to carry. With such aid it would be possible for the ordinary boats, with which vessels are always provided, to tow the crew and passengers to shore.

It would be advisable to divide a large hose for such a purpose, into a number of separate air cells, to provide against the accidental rupture of any part of it. Such an accident would thus be productive of no injury, as it would allow the air only to escape from one cell.

(63.) The weight of the human body is very nearly equal to that of its own bulk of water; its magnitude, however, is subject to a small variation, caused by the action of breathing: when the lungs are inflated, the volume of the body is greater than after they collapse. It is true that in this case the weight of the body as well as its magnitude, strictly speaking, undergoes an increase; but the change of weight is comparatively small, being that of a few grains of air, which are alternately inspired and breathed out. The change of volume produces, however, a sensible effect when the body is immersed in the liquid.

When the chest is inflated with air by drawing in the breath, the body is somewhat lighter than its own bulk

of water; and, if it be immersed in that liquid, it will displace its own weight before total immersion takes place. If the head be presented upwards and incline backwards, so as to keep the mouth and nose in the highest possible position relatively to the remainder of the body, a person may float with about half the head above water when the chest is filled with air; but when he breathes out his lungs collapse, and the bulk of his chest is diminished; his neight, however, remaining the same, he must sink deeper in order to displace his own weight of water. A living body floating on water is, therefore, in a state of continual oscillation, alternately rising and sinking: this effect is increased by the inertia of the body; for when it descends it will not cease to sink exactly at that depth at which it displaces its own weight of water, but it will continue to move with the velocity it has acquired until the increasing weight of the water displaced forces it to return upwards: its alternate ascent is similarly increased. This effect may be observed by pressing a piece of cork in water to a greater depth than that at which it naturally floats; an oscillation will ensue which will continue for some time.

Hence arises one of the difficulties which are found in floating on water; for, in the alternate sinking of the body, the mouth and nostrils may be so choked as to intercept the breathing: a slight action of the hands or feet is therefore necessary to resist the tendency to sink after each expiration from the chest.

The lighter the body is in relation to its magnitude, the more easily will it float, and a greater portion of the head will remain above the surface. As the weights of all human bodies do not bear the same proportion to their bulk, the skill of the swimmer is not always to be estimated by his success: some of the constituent parts of the human body are heavier, while others are lighter, bulk for bulk, than water. Those persons in whom the quantity of the latter bear a greater proportion to the former will swim with a proportionate facility.

Sea water has a greater buoyancy than fresh water,

being relatively heavier; and hence it is commonly said to be much easier to swim in the sea than in a river: this effect, however, appears to be greatly exaggerated. A cubic foot of fresh water weighs about 1000 ounces; and the same bulk of sea water weighs 1028 ounces: the weight, therefore, of the latter exceeds the former by only 28 parts in 1000. The force exerted by sea water to support the body exceeds that exerted by fresh water by about one thirty-sixth part of the whole force of the latter.

It has been proved that in whatever position a body floats on a liquid, the same bulk must be immersed; it follows, therefore, that if a person floating raise his hand above the surface of the water, an equal portion of his head must sink. Hence the danger arising to persons drowning is increased by the involuntary effort by which they stretch out their arms.

(64.) The bodies of some animals are much lighter than their own bulk of water. Many species of birds, such as ducks, geese, swans, and water fowl generally, present examples of this. The feathers with which they are covered contribute much to their buoyancy; and, in many instances, a very small portion of their body will displace a quantity of water equal to their weight.

Fishes have a power of changing their bulk by the distension of an air vessel with which they are provided; they can thus at will displace a greater or lesser quantity of water. When they enlarge their bulk, so as to displace more water than their own weight, they rise to to the surface; and when, on the other hand, they contract their dimensions, so as to displace less water than their own weight, they sink to the bottom.

When a human body is first drowned, the air being expelled from the lungs, it is heavier, bulk for bulk, than water; and, therefore, remains at the bottom. The process of decomposition subsequently produces gases, by which the body is swelled and increased in bulk so much, that it displaces more water than is equal to its own weight, and therefore rises to the surface. When

the vessels, containing the gases thus generated, burst, the body will again contract its dimensions and sink.

(65.) Philosophical toys are constructed on this principle. A small glass vessel is constructed in the form of a balloon, which is hollow, and the lower part of which is open; it is immersed in water with its mouth downwards, so that the air included within prevents the water entering beyond a certain point. This balloon is placed floating on the surface of water contained in a deep glass jar filled nearly to the top; a bladder is tied on the top, so as to confine a small quantity of air between it and the surface of the water in the jar. A pressure being excited by the hand on the bladder, is transmitted by the air under the bladder to the water, and the water again transmits it to the water included in the balloon; this air being elastic, yields to the pressure and contracts its dimensions, allowing a greater quantity of water to enter the balloon: the balloon thus displaces a less quantity of water, while its own weight, including the air in it, remains unaltered. At length the water it displaces is less than its own weight, and it sinks slowly to the bottom of the jar. When the bladder is relieved from the pressure, the air in the balloon again expands, the water displaced by it increases, and it slowly ascends to the surface.

A solid having air enclosed, which is exposed to the pressure of the liquid in which it is immersed, may arise to the surface if it be immersed only to a certain depth; but if it be immersed to such a depth that the hydrostatic pressure of the surrounding liquid so condenses the air within that the solid displaces a less quantity of liquid than its own weight it can no longer rise. A diver who plunges in the sea is lighter when he enters than his own bulk of water; but, if he proceed to a certain depth, his dimensions will be so contracted by the pressure of the sea that he will displace a less quantity of water than his own weight, and, therefore, cannot rise by mere buoyancy, but must ascend by the exertion of his limbs, swimming, as it were, upwards.

It is known that in the process of congelation, water undergoes a considerable increase of bulk; thus a quantity of water, which at the temperature of 40° measures a cubic inch, will have a greater magnitude when it assumes the form of ice at the temperature of 32°. Consequently ice is, bulk for bulk, lighter than water. Hence it is that ice is always observed to collect and float at the surface.

A remarkable effect produced by the buoyancy of ice in water is observable in some of the great rivers in America. Ice collects round stones at the bottom of the river, and it is sometimes formed in such a quantity that the upward pressure by its buoyancy exceeds the weight of the stone round which it is collected, consequently it raises the stone to the surface. Large masses of stone and ice are thus observed floating down the river to considerable distances from the places of their formation.

CHAP. VI.

OF DIFFERENT LIQUIDS IN COMMUNICATING VESSELS.

LIGHTER LIQUIDS FLOAT TO THE TOP. — OIL, WATER, AND MERCURY. — CREAM OF MILK. — INGREDIENTS OF THE BLOOD. — OIL AND SPIRITS. — PROOF SPIRITS. — WATER AND WINE. — WATER IN THE DEPTHS OF A FROZEN SEA LESS COLD THAN AT THE SURFACE. — A LIQUID MAY BOIL AT THE SURFACE, WHILE THE LOWER PARTS ARE COLD. — METHOD OF APPLYING HEAT TO BOIL A LIQUID. — METHOD OF APPLYING ICE TO COOL WINE. — DIFFERENT LIQUIDS IN A BENT TUBE. — METHOD OF RAISING WATER BY IMPREGNATING IT WITH AIR.

(66.) All that has been proved in the previous chapter respecting the ascent and descent of solids in liquids is equally applicable to two or more liquids in the same vessel. In this case, providing that no chemical combination takes place between the liquids, the lighter will always ascend and remain above the heavier. And if more than two liquids be contained in the same vessel, they will severally arrange themselves in the order of their weights, the lighter being above the heavier.

If oil and water be mixed by shaking them in the same bottle, they will speedily separate when the bottle is placed at rest on the table. The particles of the oil will rise, and those of the water fall, until they are totally disengaged from one another; the water occupying the lower part of the vessel and the oil the higher. If mercury, which is heavier than water, be added to the mixture, it will take the lowest place, leaving the water immediately above, and the oil at the top.

These effects are only manifestations of the principle which has been already so fully explained in its application to solids immersed in liquids. A particle of a lighter liquid immersed in a heavier displaces a portion of that heavier equal to its own bulk, and it is urged upwards by a force equal to the difference between its

weight and the weight of the heavier liquid which it displaces. What is true of one particle is equally true of any number; and when two liquids of different weights are mixed together, we may consider the particles of the lighter to be urged upwards, by the predominating effort of the heavier to sink to the bottom.

There are numerous familiar effects which are manifestations of the principle now explained. When a vessel of milk is allowed to remain a certain time at rest, it is observed that a stratum of fluid will collect at the surface, differing in many qualities from that upon which it rests. This is called *cream*; and the property by which it ascends to the surface is its relative levity: it is composed of the lightest particles of the milk, which are in the first instance mixed generally in the fluid; but which, when the liquid is allowed to rest, gradually rise through it, and settle at the surface.

When blood taken from an inflamed patient is suffered to remain a sufficient time in a vessel at rest, it resolves itself into three parts, which arrange themselves in the order of their weights one above another. The heaviest element, called *serum*, settles at the bottom, above that a lighter substance, called *coagulum*, arranges itself, and at the top the lightest component part, called *buff*, is collected.

If oil, which rises to the surface of water, be mixed with alcohol or some other spirits, it will settle at the bottom. A weaker spirit is heavier, bulk for bulk, than a strong one, and its strength may be so far reduced that it will no longer float on the surface of oil, but will sink below it; this is the test which fixes the strength of *proof-spirit*. All spirit which floats upon oil is said to be *above proof*.

As all spirits are lighter than water, they will float upon its surface if they be not mixed through it. But if these liquids be mixed, chemical effects will ensue, which will resist that separation which mechanical causes would produce. If a vessel be half filled with water, and that a piece of paper be laid upon its surface, and

wine be poured over the paper, on carefully removing the paper so as to produce the least possible agitation in the liquids, the wine will continue to occupy the upper part of the vessel, and the water the lower. But if, on the other hand, the vessel be first filled with wine, and the water be similarly poured over it, it will immediately sink through the wine, and the liquids will be mixed, their chemical affinity resisting the tendency of the wine to rise to the top. By the following contrivance, however, the wine and water may be made to change places without intermixture.

Fig. 48.

Let A and B, *fig.* 48., be two vessels connected by a narrow neck C. Let E be a tube from the lower vessel B to the upper vessel A, and let D be a tube from the upper vessel A to the lower vessel B, and let all communication between the vessels except by these tubes be stopped. Let B be filled with water to the neck C, and let A be filled with wine to a level above the mouth of the tube E. The water in the lower vessel, and the wine in the upper vessel, will thus be in contact in the neck C, but they will continue separate, the wine will not descend into the water. The vessels being now emptied, let the lower vessel be filled with wine and the upper one with water. The water which fills the upper vessel, pressing on the wine in the tube D, will force it down, and compel it to ascend in E. The wine in the lower vessel will thus be gradually discharged in the upper, while the water in the upper will be deposited in the lower. If the lower part of the vessel be concealed or formed of any substance not transparent, such a vessel is used as a toy, by which water is apparently converted into wine.

The fact that water at temperatures between the freezing point and 40° is lighter, bulk for bulk, than at higher temperatures, has been already noticed. It follows, therefore, that water at this temperature will float upon the surface of water at higher temperatures. Hence it follows that the water immediately beneath a

sheet of ice floats above the less cold water which is at greater depths; and this liquid being a bad conductor of heat, the lower region of a frozen sea may be at a very moderate temperature, while the most intense cold prevails above. Animal life may be thus preserved in the lower parts of the deep, which would be destroyed if the heat, thus confined there, were permitted to escape. The lighter stratum of fluid under the congealed surface forms a barrier, in a great degree, impervious to the heat, and thus preserves the marine animals which are in the lower parts of the sea.

If heat be applied at or near the surface of water contained in a vessel, the higher strata of the liquid may be made to boil, while the lower parts retain their original temperature. For, like all other substances, water expands when heated, and therefore becomes lighter; consequently, the hot water at the surface will not descend into the lower part of the vessel, and the imperfect manner in which the liquid conducts heat prevents the lower strata from receiving any effect from the increased temperature of the surface.

On the other hand, if the water in the bottom of a vessel be heated, it will be rendered lighter by expansion than the cold water which is above it; and, conformably to the principles already explained, it will ascend through the cold water above it in the same manner as the particles of oil would ascend from the bottom of a vessel of water and float at the top. The lower and higher strata thus interchange places, and the latter in its turn becoming heated more than the former again interchanges places with it. Thus so long as the lower strata continue to receive increased temperature, a constant interchange of position will be produced between the higher and lower strata of the liquid: ascending and descending currents will be constantly maintained until the liquid boil.

This effect may be exhibited in such a manner as to be easily observed. Let a tall glass jar be filled with cold water, and let a small quantity of amber reduced

tó powder be thrown into it. Amber being very nearly equal in weight, bulk for bulk, to water, the difference of weight produces so slight a tendency in it to sink, that this tendency is overcome by the molicular attraction of the water for its particles; it, therefore, remains suspended in the liquid, being mixed through every part of it, and is distinctly visible to the eye. Let the jar be now immersed to a small depth in a vessel of hot water, so that the lowest strata of water in the jar may be gradually heated. The water at the bottom of the jar will be observed continually to ascend, carrying up the particles of amber with it, while the upper strata descend. This will be rendered visible by the ascent and descent of the particles of amber.

In like manner if the jar be totally submerged in another glass jar of boiling water, the portion of water near the surface of the submerged jar will first become heated, and will therefore be lighter than the water near its centre. In this case we shall observe a current of amber particles continually ascending near the surface of the submerged jar, while a contrary current is constantly maintained near its centre. The heated water near the surface thus continually interchanges places with the colder water in the centre.

When a liquid has attained a certain temperature, which is always the same in the same liquid, but which differs in different liquids, it will be incapable of any further increase. If the vessel which contains it be exposed to fire, or any other source of increased heat, the effect produced upon the liquid will not be to make it hotter, but to convert it into vapour or steam. If the lowest stratum, as is usually the case, be that which is exposed to the fire, the water in it will be first converted into steam, which will be produced in bubbles at the bottom of the vessel. These being many hundred times lighter than the liquid will rise with great rapidity to the surface, where they will escape into the air, producing that agitated appearance on the surface of the liquid which is called boiling or ebullition.

From the above reasoning it will be evident, that if fire be applied for a sufficient length of time to the lowest part of a vessel containing a liquid, the whole of the liquid in the vessel, however remote it may be from the fire, will ultimately become heated; for the water occupying the lowest strata will continually ascend by its increased levity, until the whole mass of liquid receives the highest temperature of which it is capable. An apparatus for the warming of houses is constructed on this principle. A small metal boiler, made water tight, is placed upon a fire in the lowest part of the building. A tube proceeds from this vessel, and is carried through all the apartments which are required to be heated, passing along the walls in any convenient direction. The tubes and boiler are completely filled with water. A fire is kept lighted under the boiler so as to heat the water which it contains. As this becomes lighter by increased temperature, it ascends through the tubes, and is replaced by the colder water descending; and this continues until the water in all the tubes is raised to the boiling point: the metal of the tubes becomes ultimately heated to the temperature of boiling water, and imparts an increased temperature to the air which surrounds them.

The same tubes being furnished in proper places with cocks will supply hot water for baths and other domestic purposes in every part of the building.

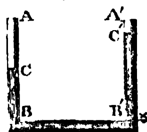
The same reasoning which proves that to heat a liquid the source of heat should be applied to the lowest strata, necessarily leads to the conclusion, that to cool a liquid the source of cold should be applied to the highest strata. If the lowest part of a vessel containing a liquid be plunged in melting ice, the liquid near the bottom, imparting its heat to the ice, will be cooled, and being rendered heavier than the liquid above, it will remain at the bottom. In this case the only part of the vessel which will be cooled will be the lower strata; the upper parts will maintain their former temperature. But if the highest stratum of the liquid in the vessel be sur-

rounded by melting ice, it will be first cooled, and being rendered thereby heavier will sink to the bottom, displacing the warmer liquid below. This process will be continued so long as the highest stratum has a temperature above that of the cooling application.

Hence it appears, that when ice is used to cool wine, it will be ineffectual if it be applied, as is frequently the case, only to the bottom of the bottle; in that case the only part of the wine which will be cooled is that part nearest the bottom. As the application of ice to the top of the bottle establishes two currents, upwards and downwards, the liquid will undergo an effect in some degree similar to that which would be produced by shaking the bottle. If there be any deposit in the bottom whose weight, bulk for bulk, nearly equals that of the wine, such deposit will be mixed through the liquid as effectually as if it had been shaken; in such cases, therefore, the wine should be transferred into a clean bottle before it is cooled.

(67.) We have shown that the same liquid, in communicating vessels, will always stand at the same level; this property depends on the circumstance of columns of equal heights having equal weights: consequently it follows, that if communicating vessels contain different liquids, of which equal columns have different weights, they will not stand to the same level. The vessel which contains the lighter liquid will have its surface at a greater height, because a column of equivalent weight to the heavier will necessarily be higher; and not only so, but higher exactly in that proportion in which the liquid is lighter. This will be more clearly understood by the following illustration:—

Fig. 49.



Let B B', *fig.* 49., be a horizontal tube connected with two upright tubes, A B and A' B', and let a stopcock be placed at B'. Let the horizontal tube B B' be filled with quicksilver, and let two liquids lighter than quicksilver, and which, bulk for bulk, have different weights,

be poured into the tubes A B and A′ B′ to any heights as C and C′. It is evident that the stopcock B′ is pressed downwards by the weight of the column C′ B′: also it appears that the mercury at B is pressed downwards by the weight of the column C B; and this pressure is transmitted by the mercury to the stopcock B′. The stopcock is, therefore, under the effects of two opposite pressures, viz. the weight of the column C′ B′ downwards, and the weight of the column C B upwards. If either of these pressures be greater than the other, a corresponding motion would take place on opening the stopcock; thus, if the weight of the column C′ B′ were greater than that of the column C B, the mercury would be pressed towards B, and the liquid in C′ B′ would enter the horizontal tube. If, on the contrary, the weight of the column C B were greater than that of C′ B′, the upward pressure at B′ would be greater than the downward; and, on opening the stopcock B′, the mercury would be pressed up the tube B′A′. In order, therefore, that the liquids in the two tubes should be in equilibrium, on opening the stopcock it is necessary that the weights of the columns in the upright tubes should be equal; in which case, whether the stopcock is open or closed, equilibrium will be preserved.

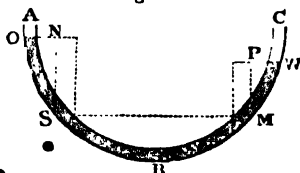
From this conclusion it is apparent, that the surfaces C and C′ will not stand at the same level unless the liquids in the upright tubes have, bulk for bulk, the same weight; for if one be lighter than the other, bulk for bulk, it will, in the same proportion as it is lighter, require a greater height of column to give the same weight as the heavier liquid. Thus, if a pint of the lighter liquid weigh forty ounces, and a pint of the heavier weigh fifty ounces, it is evident that a column of the latter, forty inches in height, will exert the same pressure as a column of the former fifty inches in height; or in general it may be stated, that the two columns will exert equal pressures, providing that the proportion of the height of the column of heavier liquid shall bear,

to the height of the column of lighter liquid, the proportion of forty to fifty, or of four to five.

The communicating vessels in this case are represented as tubes of equal magnitudes; but, by comparing the conclusions at which we have just arrived with the reasoning used in (38.), it will be apparent that these inferences may be generalised; and that liquids, contained in any communicating vessels of whatever shape or position, will, when in equilibrium, have their surfaces at heights determined on the principles just laid down. The surfaces of the lighter liquids will be more elevated than those of the heavier in proportion as their weights, bulk for bulk, are less.

Let A B C, *fig.* 50., be a bent tube, open at the ends

Fig. 50.



A and C, and let oil and water be poured into it; let S be the surface of the water on which the oil rests, and draw the horizontal line S M. If the oil were removed from the leg A B, and the water above M also removed from the leg C B, the water below S M in the curved tube would remain in equilibrium, since the surfaces S M are at the same level. That this equilibrium may be continued when the oil is introduced into the leg A B, and the additional water into the leg C B, the pressures which these liquids excite at S and M must be equal; but the pressure at S is equal to the weight of a column of oil, whose height is S N, and the pressure at M is equal to the weight of a column of water, whose height is M P, as has been proved in (37.) (38.), &c. Hence the height S N must be greater than the height M P, in the same proportion as water is heavier than oil; and

a similar conclusion may be obtained with respect to any other liquids.

The property by which a short column of a heavier fluid will support a long column of a lighter one has been used by M. Dectot in machines invented by him, called hydreoles, for the purpose of forcing water above its original level. In these machines water is, by an ingenious contrivance, mixed with air; the mixture is of course lighter, bulk for bulk, than pure water, and a short column of the latter will support a long one of the former. There are different methods of impregnating the liquid with air; one in particular is by forcing the air into the water by a bellows through a plate pierced with a number of very small holes, like the cover of a sand bottle, or the rim of a gas burner; the air thus enters the water in extremely minute globules, so that their buoyancy is insufficient to overcome the molecular force which attaches them to the particles of the water. An upright tube containing the water thus impregnated with air communicates with a reservoir containing pure water; and the liquid in this upright tube will stand as much higher than the water in the reservoir as pure water is heavier than the water surcharged with air. The reservoir answers the double purpose of supplying the water and pressing it up in the tube; for, as it passes from the reservoir to the tube, it encounters the jets of air which charge it.

CHAP. VII.

EQUILIBRIUM OF FLOATING BODIES.

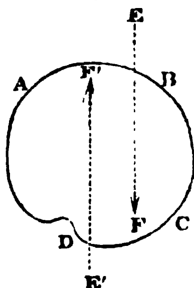
CONDITIONS OF EQUILIBRIUM. — CASES OF STABLE, INSTABLE, AND NEUTRAL EQUILIBRIUM. — EXPERIMENTAL PROOF. — FEAT OF WALKING ON THE WATER. — LIFE PRESERVERS. — STABILITY OF SHIPS. — POSITION OF CARGO. — BALLAST. — DANGER OF STANDING UP IN A BOAT. — INCLINATION OF A SAILING VESSEL. — HOW AVOIDED IN STEAM VESSELS.

(68.) THE circumstances under which a solid will sink, rise, or be suspended in a liquid, have been fully explained in chap. iv. But these circumstances are insufficient to determine the exact state of the body with respect to motion or rest. A body may be in equilibrium with reference to any perpendicular motion towards or from the surface of the liquid; that is, it may neither rise nor sink, but yet it may not be in a state of absolute rest. Again, to say that a solid rises or sinks in a liquid with a certain force, does not describe its state with exactness: while it rises or while it sinks, it may also have motions of another kind; such as motions in an oblique direction, or rotatory motions. To explain fully, therefore, all the conditions which affect the state of a solid immersed, all the particulars here alluded to must be investigated.

The motions of which a solid body is susceptible may in general be reduced to two, viz. progressive motion, and rotatory motion. In progressive motion, all the particles of the solid are carried forward in parallel lines with the same speed: in rotatory motion, the body remains in the same place, but turns round some point within it as a centre. Let A B C D, *fig.* 51., be a solid body, and let E F and E′ F′ be the directions of two forces acting on it in parallel and contrary directions; if these two forces be equal, it is evident that they cannot give the body any motion in the direction E F or

in the direction E′ F′; for, since the forces are equal, there is no reason why the body should move in the one direction rather than the other. Such a supposition

Fig. 51.



would necessarily involve some distinction between the two forces, whereas no such distinction exists. A force of a pound weight drawing a body towards the north, and another force of the same weight drawing the same body towards the south, evidently cannot produce motion in either of these directions.

The effect of two such forces as are supposed to act in *fig.* 51. will be to give the body a motion of rotation in the direction A B C D.

But if the equal forces, instead of acting in parallel lines, acted in the same right line, and in contrary directions, then they would be mutually neutralised, and the body would be kept at rest.

If the forces represented in *fig.* 51. were unequal, then the body would receive a progressive motion in the direction of the greater force; but as a consequence of the forces not being in the same straight line, the body would also receive a motion of rotation in the direction A B C D. It would be carried along in the direction of the prevailing force, and during its progress it would spin or revolve.

If, however, the unequal and contrary forces act not in parallel lines but in the same line, then no rotation

will ensue, but the body will advance with a progressive motion only according to the direction of the prevailing force.

These general mechanical principles being clearly understood, all the effects produced by the immersion of a solid in a liquid may be rendered easily intelligible.

Let us suppose a solid body of any proposed figure immersed, whether totally or partially, in a liquid.

A downward force equal to the weight of the solid is opposed, as has been shown in chap. v. by an upward force equal to the weight of the liquid which the solid displaces. If either of these forces be greater than the other, the body will have a tendency to rise or sink proportional to their difference; and if they be equal, the body will be in equilibrium as to its ascent and descent in a perpendicular direction: but it still remains to be decided, whether the solid may not move in the liquid without either rising or sinking.

To determine this it will be necessary to ascertain the exact directions of the two forces downwards and upwards which act upon the body.

The downward force being the weight of the solid, acts in a direction pointing perpendicularly downwards from its centre of gravity.* The direction of the upward force is not, however, so obvious. It is to be considered that the liquid presses upon the solid exactly in the same manner as it would press upon the liquid whose place the solid occupies. Now it is certain, that if the space in the liquid, occupied by the solid, were occupied by the liquid which the solid has displaced, that liquid would remain at rest. Consequently, the downward pressure of that liquid would be neutralised by the upward pressure of the surrounding liquid. Therefore, whatever that upper pressure be, it must be equal to the downward pressure of the liquid displaced by the solid, and it must act upward in the same line as the latter acts downward. But it is easy to perceive that the downward force of the liquid displaced by the

* Cab. Cyc. Mechanics, chap. ix.

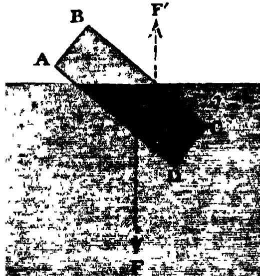
solid is equal to the weight of such liquid, and acts perpendicularly downwards from the centre of gravity of such liquid. Hence it is evident that the upward pressure which acts upon an immersed solid is equal to the weight of the liquid displaced, and that it acts directly upwards in a line from the centre of gravity of the liquid so displaced.

This may be also explained as follows: — Suppose the place which the solid occupies in the liquid to be filled by an another solid of uniform density, and whose weight is equal, bulk for bulk, to that of the liquid. Such a solid, as far as relates to any effects of weight or pressure, is equivalent to the liquid whose place it occupies; and as that liquid would in its situation remain at rest, it will also remain at rest. Hence it appears that the upward pressure upon it must be directed in the same line as that in which its weight is directed downwards; but this direction is that of the perpendicular line passing through its centre of gravity. It is evident that the upward pressure against such a solid must be the same as against any other solid, the immersed part of which occupies exactly the same place; and therefore it may be inferred generally, that the upward pressure is in the direction of a line drawn directly upwards from the centre of gravity of that part of the solid which is immersed, the density of that part being, like the liquid, supposed to be uniform.

Let A B C D be a solid immersed in a liquid, either partially as in *fig.* 52., or totally as in *fig.* 53. Let E be the centre of gravity of the solid, and let E′ be the centre of gravity of the liquid which the solid displaces. The weight of the solid acts downwards in the direction E F, and the pressure of the surrounding liquid acts upwards in the direction E′ F′. These two lines are both perpendicular to the surface of the liquid; they are in the vertical direction, and are parallel to each other. It is evident from the position of these lines, that whether the downward and upward forces be equal or unequal, they have a tendency to make the solid re-

volve or roll in the direction A D C B. If the downward and upward forces be unequal, this rolling motion will be accompanied by an ascent or descent of the solid in the liquid, according as the upward or downward

Fig. 52.



force predominates; and if they be equal, no vertical motion will accompany the revolving one.

Fig. 53.



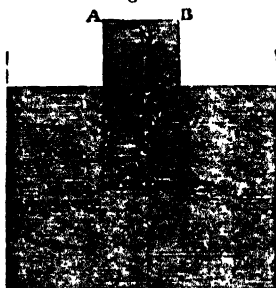
Let us now suppose the position of the solid immersed to be such, that the points E and E′ shall be in a straight line perpendicular to the surface of the fluid. In this case the point E may either be above E′, as in *fig.* 54. and *fig.* 55., or below it. In either case the contrary forces upward and downward are directly opposed to each other, and have no tendency to produce rotation. The solid will in this case sink or rise according as the upward or downward force predominates.

If the immersion be such in these cases that the liquid

displaced is equal in weight to the solid, no motion whatever will take place, and the solid will be in absolute equilibrium, neither rising, sinking, nor rolling.

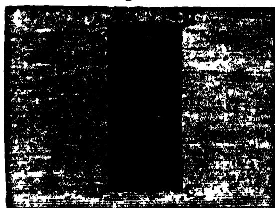
(69.) A solid immersed in a liquid may have several distinct positions of equilibrium, possessing all the various characters of stability, instability, and indifference,

Fig. 54.



explained in MECHANICS.* It has been just shown that whatever species of equilibrium the body may be in, it is an indispensable condition, that the line drawn from its centre of gravity to the centre of gravity of the liquid which it displaces, should be perpendicular to the surface

Fig. 55.



of the liquid, or in other words, that it should be in the direction of a plumb line. If this be the case, the solid will be in equilibrium; but to distinguish the peculiar kind of equilibrium in which it will be placed, it is necessary to attend to other circumstances.

* Cab. Cyc. Mechanics (159) *et seq.*

If the figure and position of the solid be such, that upon a slight change of position, by which it still displaces its own weight of fluid, its centre of gravity takes a higher position than it had when in equilibrium, then the equilibrium will be stable; because the centre of gravity having always a tendency to descend will return to its former position, and will oscillate from side to side of that position until the solid, by its friction with the fluid, at length attain a state of rest. Such is the character of stable equilibrium.

If the position of the solid in equilibrium is such that a slight disturbance, which still causes it to displace its own weight of liquid, will make the centre of gravity take a lower position, the body will not return to its former position of equilibrium, nor will it oscillate from side to side of that position as in the former case; for to do so it would be necessary that the centre of gravity should ascend, an effect which is contrary to its characteristic property.

The centre of gravity will therefore continue to descend until it gets into another position, such that the line joining it with the centre of gravity of the fluid which it displaces shall be perpendicular to the surface of the fluid. Any disturbance from this position must necessarily cause the centre of gravity to ascend, and therefore this is a position of stable equilibrium.

The shape and position of the body may be such, that, whatever be the position in which it displaces its own weight of the liquid, the elevation of its centre of gravity will be the same: in other words, any motion which it may receive, allowing it still to displace its own weight of liquid, will cause its centre of gravity to move in a horizontal plane, and, as in this case the centre of gravity neither ascends nor descends, it will rest in equilibrium in all positions. Such is the state of indifferent or neutral equilibrium.

(70.) If the solid be totally immersed, the liquid which it displaces will be equal, both in shape and bulk, to the solid, and the centre of gravity of this liquid will

therefore be the same as the centre of gravity of the solid, if the latter have like the former a uniform density; but if the solid be heavier in one part than in another, which would be the case if different parts were composed of different materials, then the centre of gravity of the solid will not be in general in the same place in which it would be if the solid were of uniform texture, and therefore will not coincide with the centre of gravity of the liquid displaced.

If the centre of gravity of the solid have that situation which it would have if the texture of the solid were uniform, then upon total immersion the points marked E and E′, in *fig.* 53., will be one and the same, and the lines E F and E′ F′ can never be parallel to each other whatever be the position of the body in the liquid, but will always be directly and immediately opposed. Hence the downward and upward forces, the directions of which are expressed by those lines, can never act in such a manner as to cause the body to revolve, but can merely give it a tendency to ascend or descend in the liquid without any other change of position. If in this case the weight of the solid be equal to that of its own bulk of the liquid, it will be suspended in equilibrium in any position whatever when it is totally submerged. In this case the solid, when totally submerged, is always in a state of neutral equilibrium.

If the centre of gravity of the solid be not in that situation which it would have if the solid were of uniform texture, then its position will not coincide with that of the liquid whose place it occupies when totally submerged. If the weight of the solid be equal to that of its own bulk of the liquid, there are in this case only two positions in which, when submerged, it will be in equilibrium. These are the positions in which the centre of gravity of the solid is immediately above and immediately below the centre of gravity of the liquid whose place it occupies. If the centre of gravity of the solid be immediately above that of the liquid displaced, it is in the highest position which the circumstances of

the case admit it to have, and therefore the least disturbance must cause it descend, which it will continue to do until it takes the other extreme position in which it is immediately below the centre of gravity of the liquid displaced. The former, therefore, is the position of instable equilibrium, and the latter of stable equilibrium.

(71.) These various effects of total submersion may be easily verified experimentally. Let a hollow brass ball be provided with a small weight within it, movable by a screw, in such a manner that the centre of gravity of the ball may be made at pleasure, either to coincide with its centre, or to take other positions at any distance from its centre; and let the weight of the ball be so adjusted that it shall be equal to the weight of the liquid which it displaces.

First, let the centre of gravity of the ball be so adjusted as to coincide with its centre. It is evident that it will thus have the same position as the centre of gravity of the liquid which it will displace. If the ball be now totally submerged in the liquid, it will be found that it will rest in any position whatever in which it is placed; whatever point of the ball be presented downwards will remain so.

Let the screw be now so adjusted that the centre of gravity of the ball shall be at some distance from its centre, and let the ball be totally submerged. It will be found, if such a position be given to the ball, that its centre of gravity shall be immediately below its centre, the ball will remain steady in its position; but if it be placed with its centre of gravity presented in any direction sideways, the ball will turn on its centre, and the centre of gravity will fall towards that position in which it is immediately under its centre, and the body will vibrate until the friction of the fluid reduces it to a state of rest. If the ball be submerged in such a position that its centre of gravity shall be immediately above its centre, then the ball will remain in equilibrium for an instant, while it sustains no disturbance; but its

balance will be tottering and instable, and will almost immediately be lost, and the ball will reverse its position, throwing its centre of gravity into the situation immediately opposite to that in which it was placed.

(72.) But the conditions of stability are of much greater interest and practical importance in their application to solids which are lighter, bulk for bulk, than liquids. In this case the degree of immersion which produces equilibrium is always partial, and the centre of gravity of the liquid displaced does not, as in the former case, coincide with the situation which the centre of gravity would have if the texture of the solid were uniform. Therefore a solid of uniform texture, or having its centre of gravity in the same situation as one of uniform texture, will not float in equilibrium in every position. It will only be in equilibrium when the centre of gravity of the liquid displaced shall be either immediately above or immediately below the centre of gravity of the solid. In this case the situation of the centre of gravity of the liquid displaced will depend on the shape of the body, and the part of it which is immersed.

Of all the various positions which can be given to a solid lighter than the liquid, in which it will displace its own bulk of the liquid, if there be one in which the centre of gravity will be lower than in any of the others, that one will be a state of stable equilibrium, and it will be one which the body will always endeavour to attain whatever other position may be given to it.

The shape of a body may be such, that in whatever position it floats its centre of gravity will be at the same depth; such a body is always in a state of neutral equilibrium; the least disturbing force will cause it to change its position, and it will remain in any new position which may be given to it.

Let the hollow brass ball already described have its weight so adjusted that it shall be lighter, bulk for bulk, than water; and let the screw be moved until its centre of gravity coincides with the centre of the ball. From

the round form of the ball it is evident that, in whatever position it is immersed, it will be at the same depth when it has displaced its own weight of water. Therefore its centre of gravity will in this case be at the same height or depth in every possible position in which it can float. It will be found, therefore, that it will float on the water steadily in any position in which it is placed; it will be in a state of neutral equilibrium.

Let the screw be now so adjusted as to remove the centre of gravity from the centre of the ball, it will be found that it will only float steadily when the centre of gravity is immediately below the centre of the ball; it will turn from any other position, and settle itself into this. If it be placed so that the centre of gravity is directly over the centre of the ball, the equilibrium will be momentary, and upon the slightest change of position the ball will be overturned, and the centre of gravity will settle itself immediately below the centre.

(73.) From these observations it will be apparent that any body, the parts of which have different weights, will only float steadily when the heavier parts are immersed; for the centre of gravity is always situated among these or near them, and therefore when it has the lowest position these must also be placed in the lower parts of the body.

A feat of dexterity has been exhibited by a person walking on the surface of water, having inflated bladders, or some other bodies which are lighter, bulk for bulk, than water, attached to the feet. The body of the exhibiter is, in this case, in a state of instable equilibrium. His centre of gravity is directly over that of the water which he displaces, and his skill consists in keeping his centre of gravity balanced in that position. This feat may be facilitated by carrying a staff with an inflated bladder tied at the end of it, by which three points of support may be occasionally commanded.

For the same reason that buoyant bodies are in this case attached to the feet, they are attached to the waist in the case of life-preservers. Their position and magni-

tude should always be regulated, so that the centre of gravity of the body shall be in the lowest position when the person is upright.

The weight of the several component parts of a ship and its cargo should always be so regulated that the centre of gravity of the whole should be at the lowest possible point, when the ship is in the upright position.

Hence arises the necessity of stowing the heaviest part of the cargo in the lowest possible position, and so that its centre of gravity shall be immediately over the keel: in that case, any inclination of the vessel on either side would cause the centre of gravity to rise, to accomplish which would require the exertion of a force proportionate to the weight of the vessel, and the height through which the centre of gravity would be so elevated. When a vessel is without a cargo and empty, the weight of the masts and rigging might raise the centre of gravity of the whole to such a height, as to render the equilibrium instable: hence in such cases it becomes necessary to introduce heavy bodies into the lower part of the vessel, to bring down the centre of gravity, and to give stability to the ship. Hence bodies used for this purpose are called *ballast*.

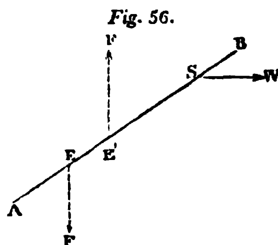
The equilibrium of a boat may be rendered instable by the passengers standing up in it; for, in this case, the weight of their bodies may place the whole in the same predicament as persons having bladders tied to their feet. The slightest disturbance, under such circumstances, would overturn the boat.

If the position of the centre of gravity of a vessel and her freight be not directly over the keel, the vessel will incline to that side at which the centre of gravity is placed; and if this derangement be considerable, danger may ensue. The rolling of a vessel in a storm may so derange the position of a loose cargo, that the centre of gravity may be brought into such a situation, that the vessel may be thrown on her beam ends and irretrievably lost.

When the centre of gravity is immediately over the

keel, a side wind acting on the sails will incline the vessel the opposite way; this inclination would be much more considerable, were it not that the weight of the vessel, acting at the centre of gravity, counteracts it, and has a tendency to restore the vessel to the upright position. The several forces which maintain the vessel in the inclined position produced by a side wind, may be illustrated as follows: — Let A B, *fig.* 56., represent the

Fig. 56.



position of the vessel; let S represent the point at which the wind acts upon the sail, and let S W represent the direction of the wind: let E be the centre of gravity of the vessel and her cargo, and let E F be the direction in which her weight acts.

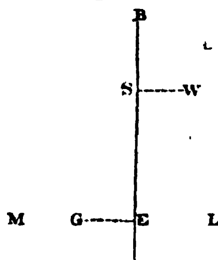
Let E′ be the centre of gravity of the water which the vessel displaces, and E′ F′ the direction of the upward pressure. If the effect of the upward and downward forces at E and E′ be considered for a moment, it will be perceived that they have a tendency to incline the vessel to the side opposite to that towards which it is inclined by the wind. By the principles of the resolution of force established in MECHANICS *, the force S W may be replaced by three others, two of which being equal, and directly opposed to the upward and downward forces at E and E′, neutralise them; and the third, acting parallel to S W, merely carries the vessel sideways perpendicular to its keel, producing what is called *lee-way*.

In sailing vessels this sideward inclination is a matter

* Cab. Cyc. Mechanics, chap. v.

of comparatively slight importance, inasmuch as it does not diminish the impelling power of the wind; but in steam vessels, in which sails are occasionally used, it is attended with considerable loss of the impelling power, one of the paddle wheels being lifted out of the water, and the other being almost, if not entirely, submerged. The upright position may, however, be generally maintained by the due management of movable weights placed on the deck of the vessel. In steam vessels, small carriages heavily laden with iron, and furnished with wheels, are usually placed on the deck, and may be rolled from side to side, or placed in the middle, so as to regulate the position of the centre of gravity according to the way in which the vessel is affected by the wind. By moving these carriages to the side of the vessel against which the wind is directed, the centre of gravity is moved from over the keel towards that side. Let E, *fig.* 57., represent the place of the

Fig. 57.



centre of gravity when over the keel, and let G represent the point to which the centre of gravity is transferred by moving the carriages to the side of the vessel; let S be the point where the wind acts upon the sail S W; the weight of the vessel acting at G, has a tendency to make it incline towards M; and the force of the wind, acting at S in the direction S W, has a tendency to make it incline towards L. These two forces counteract each other, and the vessel maintains its upright position.

CHAP. VIII.

SPECIFIC GRAVITIES.

DIFFERENT SENSES OF THE TERMS HEAVY AND LIGHT. — WEIGHT ABSOLUTE AND RELATIVE. — SPECIFIC GRAVITY. — STANDARD OF COMPARISON FOR SOLIDS AND LIQUIDS. — FOR GASES. — DENSITY. — THE IMMERSION OF SOLIDS IN LIQUIDS GIVES THEIR SPECIFIC GRAVITIES. — METHODS OF ASCERTAINING SPECIFIC GRAVITIES. — HYDROSTATIC BALANCE. — SIKES' HYDROMETER. — NICHOLSON'S HYDROMETER. — DE PARCIEUX'S HYDROMETER. — METHOD OF DETERMINING THE CONSTITUENT PARTS OF COMPOUND BODIES. — ALLOYS OF METAL. — SPIRITS. — ADULTERATION OF MILK AND OTHER DOMESTIC LIQUIDS. — HIERO'S CROWN. — PENETRATION OF DIMENSIONS.

(74.) In the preceding chapters we have had frequent occasion to compare the weights of different bodies, bulk for bulk; and not only in science, commerce, and the arts, but even in ordinary colloquial intercourse, bodies are denominated heavier or lighter, according as the weights of the same bulk are greater or less. We say familiarly that lead is heavier than copper, and that copper is heavier than cork; yet it is certain that quantities of lead, copper, and cork may be taken which have equal weights. Thus, let us suppose a pound of lead, a pound of copper, and a pound of cork, to be ascertained and set apart; it is clear that these have equal weights, and that any two of them, placed in the dishes of a balance, would maintain equilibrium. Yet still we do not cease to declare that cork is lighter than copper, and copper lighter than lead. To perceive with precision what is meant in this case, let us suppose parcels of any three distinct substances placed before us, such as quicksilver, water, and alcohol, and let it be proposed to ascertain which of these liquids is the heaviest: we shall take any measure of the quicksilver, and, having weighed it, afterwards weigh the same measure of the water and

of the alcohol successively. Having found that the measure of quicksilver is heavier than that of water, and water than that of alcohol, we shall immediately conclude that quicksilver is a heavier liquid than water, and that water is a heavier liquid than alcohol. We shall form this conclusion, even though the whole quantity of alcohol under examination shall weigh more than the quantities of the water or quicksilver.

It appears, therefore, that when the weights of substances are spoken of relatively to one another, without any reference to particular quantities or masses of them, the weights meant to be compared are those of equal bulks.

A substance is sometimes said to be heavy or light, apparently without reference to any other substance. Thus air is said to be a very light substance, and gold a very heavy one; but, in such cases, a comparison is tacitly instituted between the weights, bulk for bulk, of these substances and those of the bodies which most commonly fall under our observation. When we say that air is light, we mean that a certain bulk of air is much lighter than the same bulk of most of the substances which we commonly meet with; and when we say that gold is heavy, we mean that any portion of that metal is heavier than a portion of the same dimensions of the most ordinary substances that we meet with. This familiar use of a positive epithet to express a comparison between any quality as it exists in an individual instance with a similar quality as it exists in the average of ordinary examples, is very frequent, and not confined to the case just alluded to. We speak of a very tall man and a very high mountain, meaning that the man or mountain in question have much greater height than men or mountains commonly have. A man of twenty years of age is said to be a very young man, while a horse of twenty years of age is declared to be a very old horse, because the average age of man is much above twenty, and the average age of horses below it.

From what has been now explained, it appears that

the term weight is applied in two distinct, and sometimes opposite senses. A mass of cork may have any assignable weight, as 100 tons. This weight is truly said to be considerable, and the mass is correctly said to be *heavy;* but yet the cork which composes the mass is said, with equal truth and propriety, to be a light substance.

(75.) These two ways of considering the weight of a body may be denominated *absolute* and *relative.* The absolute weight of a body is that of its whole mass, without any reference to its bulk; the relative weight is the weight of a given magnitude of the substance compared with the weight of the same magnitude of other substances. The term *weight,* however, is commonly used to express absolute weight, while the relative weight of a body is called its *specific gravity.*

The origin of this term is obvious. Bodies which differ in other qualities are found also to differ in the weights of equal volumes. Thus a cubic inch of atmospheric air has a weight different from a cubic inch of oxygen, hydrogen, or any of the other gases. The number of grains in a cubic inch of gold is different from the number of grains in the cubic inch of platinum, silver, or any of the other metals. A cubic inch of water contains a number of grains different from a cubic inch of sulphuric acid, alcohol, or other liquids. Hence it appears that the weight of a given bulk of any substance, being different from the weight of the same bulk of other substances, may be regarded as an index or test of its *species,* and by the weights of equal bulks bodies may be separated and arranged in *species.* Hence the term *specific weight,* or *specific gravity.*

(76.) When bodies are to be compared, in respect of any common quality, a *standard* of comparison becomes necessary, in order to prevent an express reference to two bodies in every particular case. Thus, if we would express the height of any body without some standard measure, we could only do so by declaring it to be so many times as high, or bearing such a

proportion to the height of some other body. But a foot, or a yard, being known lengths, it is only necessary to state that the height of the body is so many feet, or so many yards. In like manner, if we would express the specific gravity of lead, we should state that it had such a proportion to the weight of some other body, the weight of a certain bulk of which is known. But if one substance be selected, to which, as to a standard, all others shall be referred, then the specific gravity of any substance may be expressed simply by a number which has the same proportion to one or the unit as the weight of any bulk of the substance in question has to the weight of an equal bulk of the standard substance.

The body selected as the standard or unit of specific gravity should be one easily obtained, and subject as little as possible to variation by change of circumstances or situation. For this purpose water possesses many advantages; but, in deciding the state in which it is to be considered as the standard, several circumstances must be attended to.

First, The water must be pure, because the admixture of other substances will affect the weight of a given volume of it; and since at different times, and in different places, water may have different substances mixed with it, the standard would vary, and therefore the specific gravities of substances ascertained with reference to it at different times and places would not admit of comparison. Thus, if the proportion of the weight, bulk for bulk, of gold to the weight of the water of the Seine were ascertained at Paris, and the weight of another specimen of that metal relatively to the water of the Thames were ascertained at London, the specific gravities of the two portions of metal could not be inferred unless it were previously known that the water of the Thames and the water of the Seine were composed of the same ingredients, or if not, that their relative weights, bulk for bulk, were previously determined. That the standard therefore may be invariable, it is necessary that all sub-

stances which may be combined with the water shall be extricated.

Such heterogeneous matter as may be suspended in the liquid in a solid state may be disengaged from it by filtration; that is, by passing the liquid through a solid substance whose pores are smaller than the solid impurities to be extricated. If any substances be held in solution by the water, or be chemically combined with it, they may be disengaged by distillation; that is, by raising the temperature of the liquid to a point at which the water will pass off in vapour, leaving the other substances behind; or, if those other substances vaporise at a lower heat, they will pass off, leaving the water behind: in either case the water will be separated from the other bodies with which it is combined. It is evident that this latter process of distillation also serves the purposes of the former one of filtration.

Secondly, The water being thus obtained in its pure state, and free from admixture with any other substance, it is to be considered whether there be any other cause which can make the same bulk of the liquid weigh differently at different times and places. We have already more than once alluded to the way by which bodies are affected by changes of temperature. Every increase of temperature, in general, produces an increase of bulk, and therefore causes a given volume, as a cubic inch, to weigh less. Hence, in comparing the weights, bulk for bulk, of any substances at different times or places with the weight of pure water, the results of the investigation would not admit of comparison unless the different states of the water with respect to temperature were distinctly known. In addition, therefore, to the purity of the water taken as a standard, it is expedient that some fixed temperature be adopted. It has been already explained that water, as it decreases in temperature, also contracts its dimensions until it attain the temperature of about 40°; it then again begins to expand: at this temperature of 40° it is therefore in its least dimensions, and it is known that when the water is pure, its state at this

temperature is independent of time, place, or other circumstances; it is the same at all parts of the earth, and under whatever circumstances it may be submitted to experiment.

The temperature at which pure water has its dimensions most contracted is called the state of greatest condensation, because then the mass of the liquid is reduced to the smallest possible dimensions, and its particles have the greatest possible proximity.

The weight of a given bulk of distilled water in the state of greatest condensation is, therefore, the standard of specific gravity.

As it may not be always convenient to obtain water at this temperature, when experiments on specific gravity are to be made, numerical tables have been constructed expressing the change of weight which a given bulk of water sustains with every change of temperature; so that when the specific gravity of any substance has been found with reference to water at any proposed temperature, it may be reduced by a simple process of arithmetic to that which would have resulted, had it been compared, in the first instance, with water at the temperature corresponding to the state of greatest condensation.

(77.) If the bulk of 1000 grains of pure water *, at the temperature of 40° of Fahrenheit's thermometer, be ascertained, the number of grains in the same bulk of any other body will express its specific gravity, that of water being 1000; or if the specific gravity of water be expressed by 1, the specific gravity of other substances will be expressed by a thousandth part of the former numbers. This only requires that three decimal places should be taken. Thus it is found that a volume of gold, equal in bulk to 1000 grains of water, weighs 19,250 grains. Therefore, if 1000 be the specific gravity of water, 19,250 will be that of gold; or if 1 be the specific gravity of water, the thousandth part of

* It may be convenient to remember that a cubic foot of pure water at the temperature of 60° weighs, with great precision, 1000 ounces avoirdupois.

19,250, which is 19¼, will be the specific gravity of gold; which, expressed by the decimal notation, is 19·250. A vessel which would be filled by a thousand grains of water would contain 19,250 grains of gold.

Bodies which exist in the gaseous or aeriform state are so much lighter than water, that it is generally found expedient to refer them to another standard, which has a known relation to water: their specific gravities in relation to water would be expressed by numbers inconveniently small. The standard usually selected for bodies of this form is atmospheric air; and to it the specific gravities of all bodies in the gaseous, aeriform, or vaporous state are referred, in the same manner as bodies in the solid or liquid are referred to water.

Observations respecting this standard of gaseous specific gravity may be made similar to those already given respecting the liquid standard; but, in the determination of the specific gravities of gases, there are many circumstances to be attended to of too delicate and complicated a nature to admit of being explained with any degree of detail in a treatise designed for popular use. We shall, however, notice some of them slightly as we proceed with the subject.

Atmospheric air is still more susceptible of changes in its volume, arising from change of temperature, than any bodies in the liquid or solid form. It is, therefore, the more necessary in fixing the standard, that the temperature should be settled. The temperature which has been selected for this purpose is that of melting ice, which corresponds to 32°, or the freezing point of Fahrenheit's thermometer; this being a point which is independent of the arbitrary divisions of thermometers in different countries.

The only cause which can affect the dimensions of a given weight of pure water is the temperature to which it is exposed. Although it is not absolutely incompressible, nor inelastic, yet it will undergo no sensible change of dimension by any change of pressure to which, under ordinary circumstances, it is liable. Therefore, in fixing

the state in which it is to be regarded as a standard of specific gravity, all variation of external pressure is disregarded. The case is, however, altogether different with atmospheric air, which is sensibly affected in its dimensions even by the slightest change in external pressure. While the temperature of this fluid remains the same, the dimensions which a given weight of it occupies may be subject to changes, almost without any assignable limit, and independently of any change of temperature. To fix the state of atmospheric air in which it shall be considered as a standard of specific gravity, it is necessary to declare the amount of the pressure to which it is subject. The pressure selected by Biot, who has investigated the specific gravities of gases with great success, is one which is equal to the pressure of the atmosphere when the barometer stands at six hundredths of an inch below 30 inches.*

The weight of atmospheric air and other gases is also affected by the quantity of moisture which they hold suspended. An instrument, called an hygrometer, has been contrived for the purpose of showing the relative state of gases with respect to this moisture. A due attention to the indications of this instrument is therefore also necessary to settle the state in which atmospheric air is to be regarded as the standard.

The state of the standard being then settled, the dimensions of 1000 grains of atmospheric air are determined. The number of grains, and fractions of a grain, of any other gases filling the same dimensions, will express their specific gravities, that of the standard being 1000. In order to ascertain the specific gravity of any gas with reference to water, it is only necessary to consider the specific gravity of the standard, atmospheric air, in reference to water. A portion of the former, equal in bulk to 1000 grains of the latter, will weigh one grain and 22 hundredth parts of a grain.

* This will be more easily comprehended after our treatise on Pneumatics has been studied.

(78.) From all that has been explained, there are several inferences which may be made respecting the relation between the weights and bulks of bodies, which will be found useful in all investigations which relate to specific gravity.

If two bodies have equal magnitudes, their absolute weights will be in the same proportion as their specific gravities. Thus, suppose a certain bulk of copper weighs 7600 ounces, and the same bulk of brass weighs 7824 ounces, then the specific gravities of the two metals will be in the proportion of these two numbers, because both are related to the same standard, viz. water; and, in fact, the magnitude of 1000 grains of water is equal to that of 7600 grains of copper, and to 7824 of brass.

If two bodies have equal absolute weights, then their specific gravities will be in what is called the inverse proportion of their magnitudes; that is, the body which has the greater magnitude will have a specific gravity as much less than the other as its magnitude is greater. Suppose A and B are two bodies of equal weight, the dimensions of A being twice those of B. If A be divided into two equal parts, each will have a bulk equal to that of B, and therefore the specific gravities of the two bodies will be in the same proportion as the weight of half of A is to the weight of B. But the weight of B is equal to the weight of A, and therefore the specific gravity of A is in the same proportion to that of B as the weight of half A is to its whole weight. Hence the specific gravity of A is half the specific gravity of B, while the dimensions of B are half the dimensions of A. Thus the dimensions and the specific gravities of bodies are oppositely related when their absolute weights are the same.

From the two properties just explained, it appears that the specific gravity of bodies may be ascertained either by determining the exact dimensions of quantities which have equal weights, or the exact weights of quantities which have equal dimensions.

(79.) It has been seen that the specific gravity of

every body changes with its temperature, because the change of temperature necessarily infers a change of dimension. But an enquiry naturally presents itself: does not the increase of dimension, produced by imparting heat to a body, arise from the body receiving an additional quantity of matter insinuated through and among its particles, so that in its altered state it ought to be viewed not as the original mass with increased dimensions, but as a compound of the original body, and a new portion of matter added thereto? This enquiry is tantamount to the question, whether the principle of heat be material? Nothing has been supposed in this case to be imparted to the body except heat; and the heat so imparted has at least exhibited one essential quality of matter, viz. the occupation of space, since it has forced asunder the constituent particles of the original body, which it has penetrated, and compelled them to stand at a greater distance to make way for its admission. It is true that this effect may be imagined to be produced in other ways beside supposing the particles of heat to be material; but, however it be produced, the fact is certain, that when heat penetrates the dimensions of a body, or, if we may be allowed the phrase, when it is mixed with a body, the dimensions of the compound suffer an increase in the same manner as the dimensions of any two fluids, as water and alcohol when mixed together are greater in bulk than the water was existing separately.

The question, whether the increase of magnitude, caused by raising the temperature of a body arises from its having received any addition of a material substance to its mass, can only be decided by previously fixing some one quality which will be regarded as inseparable from matter, and therefore the presence or the absence of which being ascertained will decide the presence or the absence of the additional portion of matter under enquiry.

The quality which seems best adapted for such a test is weight; and the question, whether the increased di-

mensions of a heated body proceeds from its having received any increase of ponderable matter, becomes one which is to be decided by direct experiment. Experiments to ascertain this fact have been instituted, attended by every circumstance which could contribute to ensure accurate results. The same body, at different temperatures, and therefore under different dimensions, has been accurately weighed, but no change of weight has been observed. We are, therefore, entitled to conclude that, whatever be the nature of the principle which gives increased dimensions to a body whose temperature is raised, whatever it be which fills the increased interstitial spaces from which its constituent particles are expelled, it is not a ponderous substance,—it is not one on which the earth exerts any attraction,—it is not one which if unsupported would fall, or if supported would produce any pressure on that which sustains it.

It follows, then, that the change produced in the specific gravity of a body, by any change in its temperature, depends solely upon the change produced in its dimensions, and not upon any change which takes place in its weight. We are, therefore, entitled to conclude, that the specific gravity of any body at different temperatures is *inversely* as its magnitude; that is, in the same proportion as the dimensions of the body are increased by heat, in that proportion exactly is its specific gravity diminished.

(80.) Density is the term used to denote the proximity or closeness of the constituent particles of any body to each other, and the density of a body is said to be uniform when its constituent particles are uniformly and evenly distributed through its dimensions, so that the same number of particles occupy the same space in every part of its magnitude. This is the ordinary notion of density; but it is one which, strictly speaking, is unphilosophical, because it is founded upon the supposed existence of ultimate constituent particles, or molecules of bodies, the aggregate of which form their mass. However probable the existence of such molecules may

be, they are not within the sphere of sensible observation, nor can their number or magnitude under any circumstances be ascertained. In a strictly scientific sense, the term density can be regarded as scarcely different from specific gravity. A body is more or less dense when a given volume of it contains more or less ponderous matter, and it is uniformly dense when equal magnitudes of it, however small, in every part of its dimensions have equal weights. When any body suffers a change of dimensions, either by external pressure, or by the effects of heat, since it still contains the same quantity of ponderable matter, its density must be increased in the same proportion as its bulk is diminished, or *vice versâ*. In whatever sense the term density be used this is obvious; for if it be supposed to refer to constituent particles, or atoms, it is evident that the same particles exist in the different states with a greater or lesser quantity of space between them.

If the term density be applied to bodies of different kinds, such as silver and gold, it can only be used with strict propriety synonymously with specific gravity. If it have any reference to the proximity of constituent particles, and in that sense the density of gold be declared to have the same proportion to that of silver as the weights of equal magnitudes of these metals, it will be evidently implied, that the ultimate constituent particles of the gold are equal in magnitude to those of the silver, but that nineteen particles of the former is included within a space equal to that which contains only ten particles of the latter; these numbers being taken to represent the specific gravities of those metals. The hypothesis on which such conclusions as this are founded is not necessary in physical investigation; and, indeed, the term density is rarely used, except when it is applied to the same body when subject to a variation in its dimensions.

(81.) In the effects produced by the immersion of solids in liquids we find many relations developed between the weights and bulks of the solids and of the

liquids in which they are immersed. Such effects, therefore, have a necessary connection with the specific gravities of these classes of bodies; and when properly examined, it will be found that they will lead directly to practical methods of ascertaining the specific gravities of bodies, both in the solid and liquid state.

It has been shown that a solid, heavier, bulk for bulk, than a liquid, will sink in the liquid, and that its apparent weight when immersed will be less than its true weight, by the weight of the liquid which it displaces. As the weight of the solid, and the weight which it loses by immersion, are the weights of equal magnitudes of the solid and liquid, they will be proportional to their specific gravities. Hence we infer,

1. That a solid will sink in any liquid which is specifically lighter than it.

2. That the specific gravity of the solid bears to that of the liquid the same proportion as the weight of the solid bears to the weight which it loses by immersion.

(82.) If a solid be lighter, bulk for bulk, than a liquid, it will float on the surface, displacing as much liquid as is equal to its own weight. It has been proved that when bodies have equal weights, their specific gravities are in the inverse proportion of their dimensions. (78.) Hence we infer,

1. That a solid will float on the surface of any liquid which is specifically lighter than it.

2. That the specific gravity of the solid bears to that of the liquid the same proportion as the part of the solid immersed bears to its whole dimensions.

(83.) It has been proved that if the weight of a solid be equal, bulk for bulk, to that of a liquid, it will remain suspended when totally immersed, neither rising nor sinking. Hence it appears that this phenomenon is an indication that the specific gravities of the solid and liquid are equal.

(84.) If the same solid be successively immersed in different liquids which are specifically lighter than it, the weights which it will lose by immersion in each of them

will be the weights of portions of the several liquids, equal in bulk to the solid, and therefore equal in bulk to each other. Thus if a solid, measuring a cubic inch, be successively immersed in water, sulphuric acid, and alcohol, and the weights which it loses in each be observed, we shall obtain the weights of a cubic inch of each of these liquids. These weights will therefore be in the proportion of the liquids severally. Hence we infer,—

"That a solid, successively immersed in several liquids which are specifically lighter than it, will lose weights which are proportional to the specific gravities of the several liquids."

(85.) If a solid, which is lighter, bulk for bulk, than several liquids, be made to float successively on their surfaces, it will displace portions of them which in each case are equal to its own weight, and therefore equal in weight to each other. But it has been shown, that the specific gravities of bodies having the same weight are in the inverse proportion of their magnitudes. Hence we infer,—

"That if the same body float successively on the surfaces of different liquids, the parts of it which are immersed in any two of them will be in the inverse proportion of the specific gravities of these liquids."

Thus, if the liquids be sulphuric acid and ether, the specific gravity of the sulphuric acid will have the same proportion to the specific gravity of the ether as the portion of the solid which sinks in the ether has to the portion of it which sinks in the sulphuric acid.

(86.) If several solids heavier, bulk for bulk, than a liquid, be successively immersed in it, they will sustain losses of weight equal to the weight of the liquid which they severally displace, consequently these losses will be proportional to the magnitudes of the bodies. If the solids be previously so adjusted as to be equal in weight, the specific gravities of any two of them will be in the inverse proportion of their magnitudes. (78.) Hence we infer,—

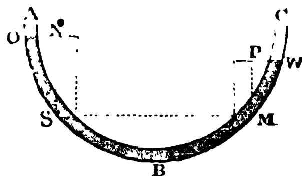
"That solids of equal weight immersed in the same liquid, which is specifically lighter than them, lose weights which are in the inverse proportion of the specific gravities."

Thus, if an ounce of silver and an ounce of gold be immersed in water, the weight lost by the gold will bear the same proportion to the weight lost by the silver, as the specific gravity of the silver bears to the specific gravity of the gold.

(87.) If several solids which are lighter, bulk for bulk, than a liquid, float upon it, they will displace portions of the liquid equal to their own weight; therefore the parts of them which will be immersed will be proportional to their weights. In this case, therefore, if the solids have equal magnitudes, the parts immersed will be in the same proportion as their specific gravities.

(88.) It has been proved, that when different liquids have been placed in communicating vessels without mixing with each other, their surfaces will rest at different levels, and that the heights of these levels respectively above the surface at which they meet are greater in proportion as the liquids, bulk for bulk, are lighter. Let A B C, *fig.* 58. be a tube as described in (67.), contain-

Fig. 58.



ing two liquids of different weights, bulk for bulk, or of different specific gravities. It has been already proved, that when they are at rest, the height S N will have the same proportion to the height P M as the weight of a given bulk of the heavier liquid to a weight of the same bulk of the lighter; hence it appears that

the heights of the surfaces O and W, of the two liquids above the level of the surface S at which they meet, are inversely as the specific gravities of the liquids. Thus if S O be oil, and S B W be water, then the specific gravity of water will bear the same proportion to the specific gravity of oil, as the height S N bears to the height P M.

(89.) The methods of practically determining the specific gravities of bodies depend upon the properties which have been just explained. The details must, however, be different for different bodies, and must be suitable to their peculiar forms and properties.

The specific gravity of a solid which is not soluble in water, and which is specifically heavier than that liquid, may be determined by observing the weight which it loses by immersion. The proportion which this weight bears to the actual weight of the solid will determine the specific gravity.

Example.—A piece of pure gold, cast and not hammered, weighing 77 grains, is immersed in water, and is observed to weigh only 73 grains; it therefore follows, that it displaces 4 grains of water. The proportion, therefore, of the weights of equal magnitudes of the metal and the water is 77 to 4, or $19\frac{1}{4}$ to 1. Hence $19\frac{1}{4}$ is the specific gravity of gold, 1 expressing the specific gravity of the standard liquid.

Example. — A piece of flint glass, weighing 3 ounces, is immersed in pure water, and observed to weigh only 2 ounces. Hence the weight of the water which is displaced is 1 ounce. The specific gravity of the glass is therefore 3.

(90.) If the solid be soluble in water, this method cannot be practised. In this case the solid may be defended from the water by a varnish, or a thin coating of wax, or some other substance not affected by the water. The specific gravity of salts and like substances may be thus found. As, however, the coating used in this case produces an increase of bulk, the solid, when immersed, will displace

more than its own bulk of water. The weight of the solid, if ascertained without the coating, will bear a less proportion to the loss of weight than it does to its own bulk of water; and therefore the specific gravity obtained from such an experiment would in this case be too small. But if the weight of the solid be ascertained after the coating is put on, then the specific gravity which is obtained is not the specific gravity of the solid but of the solid and coating together. Where great accuracy is not required, the effect produced by the coating may be neglected; but if the result is to be obtained with a high degree of accuracy, the following method is preferable: — Find the proportion of the specific gravity of the solid to that of some liquid in which it is not soluble, and which is specifically lighter than it. This may be done by observing the weight of the solid and the weight which it loses by immersion. Then find the specific gravity of that liquid with respect to water by the method which shall be hereafter explained.

If the solid consist of many minute pieces, or be in the form of powder, a cup to receive it ought to be previously suspended in the water, and accurately counterpoised.

(91.) To determine the specific gravity of a solid lighter than water, let the part immersed when it floats on water be observed, the proportion which this bears to its whole magnitude will be that of its specific gravity to the specific gravity of water. (82.)

The proportion of the part immersed, when the solid floats to its whole bulk, may be ascertained in the following manner: — Let the vessel which contains the water have perpendicular sides, and be as narrow as the magnitude of the solid will admit. Let the point on the vessel which marks the surface before immersion be observed. Let the point to which the surface rises, when the solid floats, be next observed; and, finally, let the solid be totally submerged, and the point to which the surface then rises observed. The elevations of

the surface produced by the partial and total submersion indicate the portions of the solid in each case immersed, and are therefore in the ratio of the specific gravity of the solid to that of the liquid.

There is another method of ascertaining the specific gravity of a solid lighter than water, which ought to be noticed here. Let the solid whose specific gravity is to be ascertained be attached to another which is heavier than water, and of such a magnitude that the united weights of the two will be greater than the weight of water which they displace, they will therefore sink when immersed. The weight of the whole being observed, let the weight which they lose by immersion be noted; this will be the weight of as much water as is equal in magnitude to the united bulks of the solids. Let the lighter solid be then detached, and let the weight which the heavier loses by immersion be ascertained; this will be the weight of as much water as is equal in bulk to the heavier solid. If this loss of weight be subtracted from the loss sustained by the combined masses, the remainder will be the weight of as much water as is equal in bulk to the lighter solid: the proportion of the weight of the lighter solid to this will determine its specific gravity.

(92.) There are several methods by which the specific gravities of liquids may be found.

If a solid specifically heavier than water, and also specifically heavier than the liquid whose specific gravity is to be determined, be successively immersed in water and in that liquid, the losses of weight will be proportional to the specific gravities of water and the liquid. If the number expressing the loss of weight in the liquid be divided by the number expressing the loss of weight in the water, the quotient will express the specific gravity of the liquid.

Example.—A piece of glass, immersed in sulphuric acid, is observed to lose 3700 grains of its weight. The same solid, immersed in water, loses 2000 grains; hence the proportion of the specific gravity of the sulphuric

acid to the specific gravity of the water is that of 37 to 20, or of 1850 to 1000: therefore if 1000 express the specific gravity of water, 1850 will express that of sulphuric acid.

The specific gravity of a liquid may also be found by means of a solid which is specifically lighter than it, the same solid being also specifically lighter than water. Let the solid float successively on the two liquids, and observe the magnitudes of the parts immersed, which may be done by observing the change of level if the vessels containing the liquids have equal bottoms and perpendicular sides: the parts immersed will be inversely as the specific gravities. (85.)

Example.—The same solid floats successively on water and muriatic acid, and the proportion of the parts immersed is observed to be that of 10 to 12. Hence the specific gravity of muriatic acid is 12, that of water being 10.

(93.) The specific gravities of liquids may be ascertained by observing the weights of two different solids floating on their surfaces with equal parts immersed. In this case the specific gravities will be proportional to the weights of the solids. But perhaps the most direct method of determining the specific gravities of bodies, as well in the liquid as in the gaseous state, is by actually weighing them in a flask or bottle of known magnitude. Let such a one be provided with a stopper which nicely fits it, and let it be filled with pure water and weighed, and subsequently filled with any other fluid and again weighed; if the weight of the flask be exactly known, the weight of its contents may in each case be found. In this manner the weight of air may be determined by weighing the flask first filled with air in the ordinary state, and, subsequently, after the air has been abstracted from it, by the air pump, an instrument which will be explained in a subsequent part of this volume. It is thus ascertained that a cubic foot of common atmospheric air weighs about 527 grains. This weight,

however, fluctuates from causes already alluded to, and which will hereafter be fully explained.

The empty flask may in like manner be filled with any other species of gas, and its weight relatively to that of air may be at once determined.

Instruments for the practical measurement of specific gravities.

(94.) The form and construction of instruments for determining specific gravities, vary according to the degree of accuracy required in the results, and according to the nature of the bodies to which they are intended to be applied. In scientific investigations, where the most

Fig. 59.

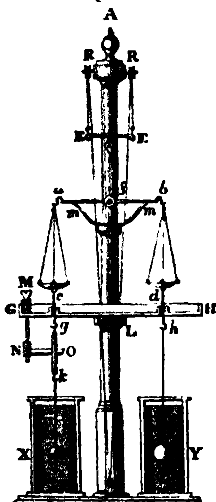
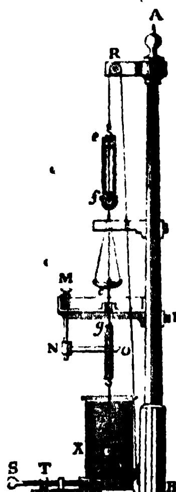


Fig. 60.



extreme accuracy is sought, the measurement of specific gravities is effected by a very sensible balance furnished with certain additions, and mounted in a manner from

which it has received the name of the *hydrostatic balance*.

A front view of the *hydrostatic balance* is represented in *fig.* 59. and a side view in *fig.* 60. The corresponding parts being marked by the same letters. A pillar A B fixed in a stand C D, supports the instrument. On the stand, placed in a horizontal position, is a screw S, which turns in a fixed nut at T. This screw is terminated by a hook, which holds the loop of a silken string, the two parts of which passing in the grooves of wheels or rollers at P are carried from thence to the top of the pillar, and there pass over the grooves of rollers at R, and their extremities finally support a horizontal arm at E. To the centre of this arm *e* a very nice balance is suspended: beneath the beam of this balance are placed rests, at *m*, so that when the beam is not in use, by turning the screw S, it will be allowed to descend upon the rests; and the knife edges, on the accuracy of which the sensibility of the instrument depends, will be relieved from pressure. The board G H, attached to the pillar immediately below the dishes, is movable on the pillar, and may be fixed in any position by means of an adjusting screw; also the nut in which the screw S turns is capable of being moved towards or from the pillar, so as to raise or lower the balance, in a greater degree than would be allowed by the play of the screw S. Thus the balance and all its accompaniments may be raised or lowered at pleasure. To the centre of the bottom of the dishes hooks *c d* are attached, from which brass wires are suspended, which pass freely through holes in the board G H. At the lower extremities of these wires are hooks *h* and *g*. To the hook *g* a graduated rod *g k* is suspended, which also terminates in a hook at *k*. The rod *g k* bears a scale of equal divisions, an index N O turns on a rod M N with a horizontal motion, and may be applied to the scale *g k* or may be removed at pleasure; this index may be also moved upwards and downwards by

means of a screw M, which plays in a nut in the board, G H. A brass ball of about $\frac{1}{4}$ of an inch diameter, is suspended from *k*, by a brass wire *k l*, of such a thickness that one inch of it will displace half a grain of water. From the hook *h* a glass bubble *i* is suspended by a horse-hair. The brass ball and the glass bubble are so adjusted that they will hang about the middle of the glass vessels X Y, in the ordinary position of the balance. If the dish *c* preponderate, the wire *k l* will become more immersed; and for every inch it sinks, the weight which draws down the dish *c* will be diminished

Fig. 59.

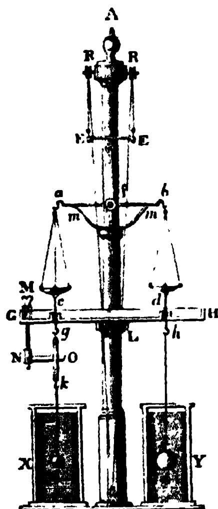
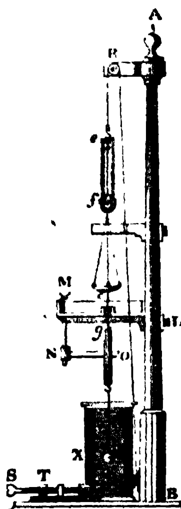


Fig. 60.



to the amount of half a grain, that being the weight which an inch of the wire loses by immersion. In like manner if *d* preponderate, the wire *k l* will be drawn up; and for every inch which is raised above the surface of the

water, an additional weight of half a grain will act upon the dish *c*.

Now suppose the balance so adjusted that its tongue points directly upwards at *e*, and that the beam *a b* is therefore horizontal; let the index N O be fixed at the middle point of the scale *g k* by means of the screw M. Suppose the scale *g k* so divided, that its middle point will be marked zero, or 0; and let each half of it, being two inches long, be divided into a hundred equal parts, being numbered upwards and downwards from the middle point. Let the substance to be weighed be placed in the dish *c* and let grain weights be placed in the dish *d*, until the number of grains nearest to its exact weight be found. Thus, suppose that it is found that 65 grains are insufficient to support the dish *c*, but that 66 grains cause the dish *d* to preponderate; the exact weight of the substance is, therefore, more than 65 grains, but less than 66 grains, and the object is to determine by what part of a grain the true weight exceeds 65 grains. Weights to the amount of 65 grains being placed in the dish *d*, the dish *c* will slowly descend; the wire *k l* will consequently become more deeply immersed in the water, and for every inch which sinks the weight of *c* will be diminished by half a grain; and therefore for every division of the scale which passes the index N O, the dish *c* will loose weight to the amount of the hundredth part of a grain. When the loss of the weight thus sustained by the dish *c* amounts to as many hundredth parts of a grain as the weight of the substance in the dish *c* exceeds 65 grains, the beam will remain in equilibrium. When this takes place, therefore, it is only necessary to observe the number of the division at which the index N O stands; that number will express the hundredth partsof a grain, by which the weight of the substance in the dish *c* exceeds 65 grains.

The weight might in like manner be ascertained by placing 66 grains in the dish *d*, and by causing it to

preponderate. In this case the wire *k l* would be drawn from the water, and for every division of the scale *g k* which would pass the index N O, the hundredth part of a grain would be added to the dish *c*; when the dish *d* would cease to descend the number of the scale marked by the index would express the number of hundredth parts of a grain by which the weight of the substance in the dish *c* falls short of 66 grains.

The effect produced by the immersion of the horse-hair from the hook *h* is here neglected, because the weight of the water, which a small portion of its length displaces, does not exceed a fraction of a grain much smaller than any weight here taken into account.

The weight of the substance being thus ascertained in air, it is next ascertained in a similar manner by immersion in the jar Y, and the loss of weight in water is thus obtained. The specific gravity may thence be inferred as explained in (89.).

To prevent the adhesion of water to the wire *k l* it is previously oiled, and the oil gently wiped off, so as to leave a thin film covering the wire.

If the body whose specific gravity is under investigation be a liquid, it must be contained in a glass vessel, carefully stopped, and completely filled. The weight of the glass vessel, empty, is first ascertained by the balance, and then its weight, when filled with water, and immersed in water; by this means the weight of the glass will be accurately ascertained, and also the weight which the glass loses by immersion in water. When the bottle is filled with the liquid, the weight of the bottle is ascertained, from which the weight of the glass being subtracted, leaves a remainder which is the exact weight of the liquid. The bottle filled with the liquid is now weighed, immersed in water, and the loss of weight is observed. From this loss, let the loss of weight sustained by the glass alone be substracted, and the remainder will be the weight of a quantity of water equa in bulk to the liquid contained in the bottle. The spe-

cific gravity of the liquid may thence be immediately inferred in the same manner as if it were a solid.

(95.) The apparatus and processes which have been just explained are adapted to give results of that extreme accuracy which is necessary for the purposes of science. With such views, the complexity and expense of apparatus, and the time, skill, and attention required for delicate manipulations, are matters of small importance compared with the attainment of exact results. But when specific gravities are to be ascertained for the ordinary purposes of commerce or finance, means of a more simple character must be resorted to, the use of which is attended with more expedition, and requires less skill in the operator. In such cases a degree of accuracy, exceeding a comparatively wide limit, is altogether unnecessary; and even though superior instruments were available, their results would not be more useful than those of a less degree of sensibility.

Various forms of instruments, usually called hydrometers, have been proposed for ascertaining the specific gravities of substances, and more particularly of liquids, for the ordinary purposes of commerce. The indications of these instruments all depend upon the fact, that a body, when it floats in a liquid, displaces a quantity of the liquid equal to its own weight. Their accuracy depends upon giving them such a shape, that the part of them which meets the surface of the liquid in which they float is a narrow stem, of which even a considerable length displaces but a very small weight of the liquid. Thus any error in observing the degree of immersion entails upon the result an effect which is inconsiderable.

The principle in all such instruments being, in the main, the same, it will not be necessary here to enter into farther details upon them than to describe the form and use of two or three of the most remarkable.

Sikes' Hydrometer.

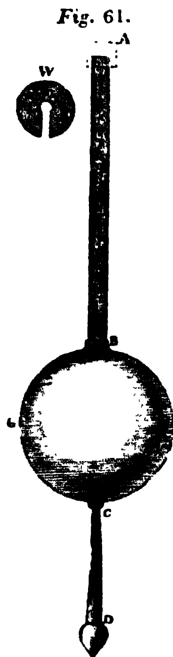


Fig. 61.

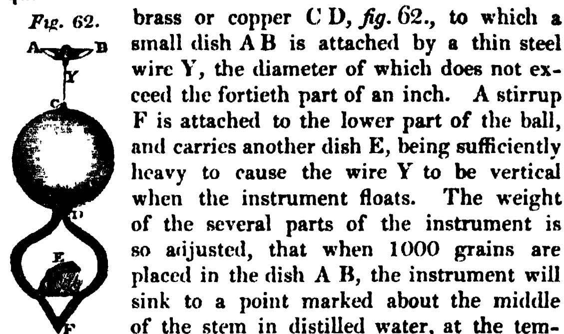
This instrument, being that which is used and sanctioned by law for the collection of the revenue on ardent spirits, &c., is entitled to particular notice. It consists of a brass ball G, *fig.* 61., the diameter of which is one inch and six tenths. Into this ball, at C, is inserted a conical stem C D, about one inch and an eighth long, terminated with a pear-shaped bulb at D, which is loaded, so as to be much heavier, bulk for bulk, than any other part of the instrument. In the top at B is inserted a flat stem B A, three inches and four tenths in length, which is divided on both sides into eleven equal parts, each of which is subdivided into two. This instrument is accompanied by eight circular weights, such as W, marked with the numbers 10, 20, 30, 40, 50, 60, 70, and 80; each of the circular weights are cut as represented in W, so as to admit the thinner part of the conical stem near C to pass to the centre of the weight; the opening is wider at the centre, so as to allow the weight to slide down the stem to D, where the thickness prevents its falling off. In using this instrument to ascertain the specific gravity of spirits, it is first plunged in the liquid, so as to be wetted to the highest degree on the scale: it is then allowed to rise and to settle into equilibrium. The degree upon the scale at the surface of the liquid indicates the quantity immersed; and, by the assistance of tables which accompany the instrument, and a thermometer by which the temperature of the spirits is observed, the specific gravity is calculated by rules which accompany the tables.

Nicholson's Hydrometer.

This instrument is susceptible of a greater degree of

accuracy than the common hydrometer observed above, and a corresponding degree of skill and attention is requisite in the use of it. It consists of a hollow ball of brass or copper C D, *fig*. 62., to which a small dish A B is attached by a thin steel wire Y, the diameter of which does not exceed the fortieth part of an inch. A stirrup F is attached to the lower part of the ball, and carries another dish E, being sufficiently heavy to cause the wire Y to be vertical when the instrument floats. The weight of the several parts of the instrument is so adjusted, that when 1000 grains are placed in the dish A B, the instrument will sink to a point marked about the middle of the stem in distilled water, at the temperature of 60°. Therefore the weight of a quantity of distilled water, equal in volume to the part of the instrument below this point, will be equal to the weight of the instrument, together with 1000 grains. To find the specific gravity of any other fluid, let the instrument float upon it, and let the weight in the dish A B be so adjusted that the instrument will be immersed as before to the division marked upon the wire. The weight of the instrument, together with the weight in the dish, will then express the weight of the liquid which the instrument displaces. Thus the weight of equal bulks of the liquid and distilled water at the temperature of 60° will be ascertained, and thence the specific gravity of the liquid inferred.

Fig. 62.



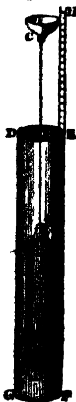
By this instrument the specific gravities of solids may be also ascertained. Let a portion of the solid be placed in the dish A B, and the instrument being made to float in distilled water at 60°, let additional weights be thrown into the dish A B until the instrument sinks to the mark upon the wire. The weight of the solid, together with these additional weights, will then, as appears from what was stated above, amount to 1000 grains; therefore, if the additional weights be subtracted from 1000 grains, the remainder will be the exact weight of the solid. Let

the solid be now placed in the lower dish E, and, as before, let weights be placed in the dish A B, until the instrument again sinks to the point marked on the stem Y. These weights, together with the weight immersed in the water, will make up 1000 grains. If, therefore, they be subtracted from 1000 grains, the remainder will be the weight of the solid in water; having obtained its weight in air and in water, its specific gravity may be obtained as in a former instance.

The wire which supports the dish A B in this instrument is so thin, that an inch of it displaces only the tenth part of a grain of water. The accuracy of its results depending, therefore, on the coincidence of the mark on the wire Y with the surface, which can always be ascertained to a very small fraction of an inch, will come within the limit of a very minute fraction of a grain. Specific gravities may thus be obtained correctly to within 100,000th part of their whole value, or to five places of decimals.

De Parcieux's Hydrometer.

Fig. 63.



This instrument, which is represented in *fig.* 63., scarcely differs from that which has been just described. A cup C is connected by a brass wire A C, about 30 inches long and a 12th of an inch in diameter, with a glass phial A B, which is loaded with shot at the bottom to keep it in the upright position. The length of the wire is such, that the phial, when loaded and immersed in spring water at a medium temperature, will sink to a point about an inch above A. When it is immersed in light river water it will sink to about 20 inches above A. The specific gravities of different kinds of water are compared by this instrument, as in Nicholson's hydrometer, by throwing weights into the dish C until the instrument sinks to a fixed point on the wire. A

graduated scale H E is attached to the side of the vessel containing the water, to mark the degrees of immersion. The sensibility of this instrument is so great, that a pinch of any substance soluble in water, or a drop of any liquid which mixes with water, being combined with the water in which it is immersed, will produce an observable effect upon its depth of immersion.

This instrument was invented for the purpose of comparing the specific gravities of different kinds of water.

(96.) The power of determining the specific gravity of bodies frequently enables us to declare their other qualities, and sometimes to detect their component parts, if, as most frequently happens, they are formed of heterogeneous materials. Thus spirits, in every form and under every variety in which they are used in commerce and domestic economy, are a mixture of alcohol with other bodies, of which water is the principal. As the value of the liquid depends upon the proportion of pure alcohol which it contains, it becomes a problem of great practical importance to determine this.

In like manner the precious metals, whether applied to useful or ornamental purposes, are generally mixed with others of a baser species in a greater or less proportion. These cheaper elements which enter into the composition of what is received for gold or silver are called *alloys*; and it is obvious that, before the value of any article formed of such a material can be determined, it is necessary to find the exact proportion of alloy which it contains.

These considerations suggest a class of problems respecting the specific gravities of compound bodies and their constituent elements, the solution of which is of great practical importance. This solution, however, does not entirely depend on mechanical principles, as we shall presently explain; and even so far as it does depend on such principles, many previous conditions are necessary to render such problems determinate.

If two bodies, whose specific gravities are known, be

mixed in a given proportion, and in their union no other effect be produced than the transfusion of the particles of each through and among those of the other, the specific gravity of the compound is a matter of easy computation. The general principle for the solution of such a problem will be collected without difficulty from an example.

Example. — Let gold and copper be united, in the proportion of 20 measures of gold to 3 of copper. The specific gravity of the gold is 1925, and that of the copper 890, the specific gravity of water being 100. Hence the calculation may be made as follows; the denomination of weight used being immaterial, providing it be the same throughout the whole investigation:—

Weight of a cubic inch of water	100
Weight of a cubic inch of gold	1,925
Weight of a cubic inch of copper	890
Weight of 20 cubic inches of gold	38,500
Weight of 7 cubic inches of copper	6,230
Weight of 27 cubic inches of the compound	44,730
Weight of one cubic inch of the compound	1,656$\frac{2}{3}$

Hence the specific gravity of the compound is 1,656$\frac{2}{3}$, that of water being 100.

If the proportion of the ingredients be given in weight, as so many grains of gold mixed with so many grains of copper, the magnitudes or measures of these weights may be computed from knowing their specific gravities, which is in fact the weight of a given magnitude. The preceding method of calculation may then be applied.

If more than two bodies be united, the principle on which the computation is conducted will be the same.

In the example just given the specific gravity of the compound was the object of enquiry, the specific gravities of the components being supposed to be given. The same method of calculation would, however, discover any of the other quantities which enter the investigation with a sufficient number of data. Thus, suppose it were required to determine one of the ingredients of

a compound substance, the nature and quantity of the other ingredient being known. Let the specific gravity of the compound be determined by the usual means, and let the quantity of the given ingredient be subtracted from the whole quantity of the compound, and the remainder will be the quantity of the required ingredient. But it is necessary to determine its specific gravity.

Example. — Let the compound body under investigation be supposed to be composed of two substances, of which gold is one; and let the total quantity of the compound be 27 cubic inches, the quantity of the gold being 20 cubic inches. Suppose that we ascertain the following results by experiment: —

Weight of 27 cubic inches of the compound	44,730
Weight of one cubic inch of gold	1,925
Weight of 20 cubic inches of gold	38,500
Weight of 7 cubic inches of the alloy . .	6,230
Weight of one cubic inch of the alloy . .	890

Hence the specific gravity of the alloy will be 890, and that being known to be the specific gravity of copper the quality of the alloy is determined.

When the quality of the alloy is known, it may be required to determine the proportion in which it is mixed with the precious metal. In this case the specific gravities of the constituent parts are supposed to be given.

Example. — Let the compound be one of gold and copper as before, the specific gravities of which are 1925 and 890.

Weight of a cubic inch of gold	1,925
Weight of a cubic inch of copper	890
Difference	1,035
Weight of a cubic inch of the compound by experiment	1,656$\frac{2}{3}$
Weight of a cubic inch of copper	890
Difference	766$\frac{2}{3}$

As the former difference 1035 is to the latter $766\frac{2}{3}$, so is 1 to the number which expresses the proportion in which the metals are mixed. Thus, by the Rule of Three: — 1035 : $766\frac{2}{3}$ :: 1 : $766\frac{2}{3}$ divided by 1035, or which is the same, $\frac{20}{27}$. Hence the proportion of gold contained in a cubic inch of the compound is 20 parts in 27, and there are, therefore, 7 parts of alloy. The demonstration of the proportion used in this solution scarcely admits of a sufficiently elementary explanation to be introduced with propriety in the text.*

If the object be to detect the exact quantity and quality of the impure or heterogeneous matter contained in any compound, it will not be sufficient that the specific gravity of the compound and that of the principal ingredient be previously known. Thus, in manufactured gold, it is not enough to know the specific gravity of pure gold, and that of the alloyed specimen under investigation, in order to determine the quantity and quality of the alloy. It is indispensably necessary, either that the specific gravity of the foreign matter intermixed with the principal ingredient be given, or that some data may be furnished by which it may be computed.

Although in the cases of alloyed metals, or adulterated liquids, it is rarely possible to detect the exact quantity and quality of foreign matter which may be intermixed, yet we may generally pronounce with certainty on the presence of some adulteration or alloy. The specific gravity of the pure substance being known, if that of

* Let x represent the proportion of gold, and y that of copper, contained in one cubic inch of the mixture. Let g be the specific gravity of the gold, c that of the copper, and m that of the mixture. The weight of gold contained in a cubic inch of the mixture is xg, and the weight of copper yc, and the weight of a cubic inch of the mixture is m. Hence we have

$$xg+yc=m$$
$$x+y=1$$
$$\therefore y=1-x. \quad \therefore xg+c\,(1-x)=m$$
$$\therefore x\,(g-c)=m-c$$
$$\therefore x=\frac{m-c}{g-c}$$
$$\text{or, } g-c : m-c :: 1 : x.$$

That is, the difference between the specific gravities of the gold and copper is to the difference between the specific gravities of the compound and copper, as 1 is to the proportion of gold which exists in a cubic inch.

the specimen under enquiry differ from it, the intermixture of foreign matter is no longer doubtful. But what that heterogeneous matter is, and in what quantity it is present, is a problem which requires the aid of other principles.

It has been already stated that spirits of every kind used in commerce, are mixtures of pure alcohol and water in different proportions, and their strength depends on the quantity of alcohol which is mixed with a given quantity of water. The indications of the hydrometer immediately betray this.

The adulteration of milk by water may always be detected by the hydrometer, and in this respect it may be a useful appendage to household utensils. Pure milk has a greater specific gravity than water, being 103, that of water being 100. A very small proportion of water mixed with milk will produce a liquid specifically lighter than water.

Although the hydrometer is seldom applied to domestic uses, yet it might be used for many ordinary purposes which could scarcely be attained by any other means. The slightest adulteration of spirits, or any other liquid of known quality, may be instantly detected by it. And it is recommended by its cheapness, the great facility of its manipulation, and the simplicity of its results.

(97.) The first notion of using the buoyancy of solids in a liquid, as means of determining the nature of their component parts, is attributed to Archimedes, the celebrated mathematician and natural philosopher. It is said that Hiero, king of Syracuse, having engaged an artist to make him a crown of gold, wished to know whether the article furnished to him was composed, according to the contract, of the pure and unalloyed metal, and yet to accomplish this without defacing or injuring the crown. He referred the question to Archimedes. The philosopher while meditating on the solution of this problem happening to bathe, his attention was directed to the buoyancy of his body in the water, and thence to

the general effect produced upon the apparent weights of solids by their immersion in liquids. The whole train of reasoning which has been followed in the preceding chapters instantly flashed across his mind. He perceived at once that the degree of buoyancy or the weight lost would betray the weight of the metal composing the crown, compared, bulk for bulk, with pure gold. He rushed from the chamber in a transport of joy, exclaiming aloud, "Eureka! Eureka!" (*I have found it! I have found it!*)

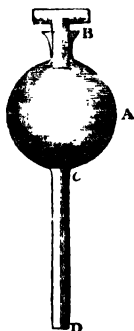
If the tale be true, the joy of Archimedes was produced not by the solution of the particular question respecting the crown, but by perceiving the important consequences to which the extension of the principle on which he had fallen must lead.

(98.) The calculations which have been just explained, for ascertaining the specific gravities of compound bodies when those of their component parts are known, proceed upon the supposition that the bulk or magnitudes of the bodies united are not altered by their combination. Thus, if ten cubic inches of gold be alloyed with seven cubic inches of copper, it is assumed that the mass of compound metal thus obtained will measure 17 cubic inches. In like manner, if a pint of water be mixed with a pint of spirits, the computed specific gravity of the mixture proceeds upon the assumption that it will measure a quart.

Experience proves this supposition to be, in most cases, unfounded. When the constituent atoms of two bodies are transfused through one another by intimate mixture, it is found that certain properties are manifested which exhibit a reciprocal relation between them, in virtue of which they are either drawn together into closer contact and compelled to occupy a less space, or are mutually repelled and made to occupy a greater space by attractive or repellant forces, which are called into operation by the contiguity of the molecules of the different bodies. In fact, it is found that equal measures of two different bodies, being combined by mixture, will

produce a compound, the measure of which will be either less or greater than twice the measure of either of the bodies so combined. Thus, a cubic inch of gold mixed with a cubic inch of copper will produce a mass of metal measuring less than two cubic inches. It follows, therefore, that the component particles of these bodies have been forced into a less space than that which they occupied separately; and, therefore, that corresponding affinities or attractive energies have been awakened by their combination. In like manner, if a pint of pure water and a pint of sulphuric acid be mixed together, the compound will measure less than a quart. This experiment may be very easily exhibited in the following manner: — Let A, *fig.* 64., be a hollow glass ball, having a neck at the top B, furnished with a ground glass stopper made exactly to fit it, and water tight, and with a long narrow tube C D proceeding from the bottom and closed at the lower end D; let this vessel be filled through the neck B with sulphuric acid as far as the top of the tube C, then let water be carefully poured in till the ball is completely filled to the neck; this liquid, being lighter than sulphuric acid, will remain in the ball resting on the surface of the sulphuric acid in the tube below. Let the stopper be inserted in the neck, so that the vessel being closed will be completely filled with the two liquids: holding the stopper firmly in its place, let the vessel be now inverted, the tube being turned upwards and the stopper downwards. The sulphuric acid will, by its superior weight, fall into the ball, and the water will rise into the tube, a partial mixture taking place by reason of the affinity of the liquids: this inversion being several times repeated, the liquids will at length be perfectly mixed. If the instrument then be held steadily with the tube upwards, it will be found that the liquids no longer fill it, but that several inches

Fig. 64.



at the top of the tube will be empty. Thus the dimensions of the liquids will be considerably contracted by intermixture; and of course the density or specific gravity will be much greater than if the liquids were mechanically united without any diminution of their volume.

The effect here described will be found to be attended with another very remarkable one. The liquids at the commencement of the process being at the ordinary temperature of the atmosphere, it will be found that after they are mixed they will acquire so great a degree of heat, that the vessel which contains them cannot be held in the hand without pain. This effect bears a close relation to the expansion of bodies by heat. If the communication of heat to a body causes its dimensions to increase, it might naturally be expected that any cause which would produce a diminution of dimension would compel the body to part with heat. Thus the condensation produced by the admixture of the two liquids is accompanied by the evolution of heat. It is sufficient barely to notice this effect here, as it will be more fully explained in another part of the Cyclopædia.

Although the method of computing the specific gravity of a mixture, upon the supposition that its constituent elements suffer no change of dimension, is inapplicable for the actual determination of the specific gravities of compounded bodies, yet such computation is not useless.* The only exact method of ascertaining the degree

* Let c and c' be the specific gravities of the component parts, and m the specific gravity of the mixture, let a and a' be the magnitudes of the component parts, and $a+a'$ will be the magnitude of the mixture. The weights of the components will be $a\,c$ and $a'\,c'$, and the weight of the mixture will be $a\,c+a'\,c'$, which is the sum of the weights of the components. but the weight of the mixture will also be expressed by $(a+a')\,m$, hence

$$a\,c+a'\,c' = (a+a')\,m.$$

$$\therefore m = \frac{a\,c+a'\,c'}{a+a'}$$

In fact, this result is nothing more than an expression denoting that the specific gravity of the compound is equal to its weight, divided by its magnitude, the magnitude being supposed to be equal to the sum of the magnitudes of the components.

In some cases the weights and specific gravities of the components are given, but not their magnitudes. Let w and w' be the weights; then $w=a\,c$, and $w'=a'\,c'$.

in which substances contract or expand their dimensions by mixture is by computing the specific gravity which the mixture would have were such change of dimension not to happen, and comparing such computed specific gravity with the actual specific gravity of the compound body observed by experiment. The process of measurement is not susceptible of the same accuracy, nor, indeed, of any degree of accuracy sufficient for scientific purposes: were it so, however, it would scarcely be so simple as the comparison of the computed and observed specific gravities. The quantities of the two substances mixed should be accurately measured before mixture, and the measure of the compound should be afterwards accurately ascertained. The difference between the sum of the measures of the constituent parts and the measure of the whole would give the contraction or expansion produced by their combination.

Therefore $a = \frac{w}{c}$ and $a' = \frac{w'}{c'}$ Hence

$$m = \frac{w+w'}{a+a'} = \frac{w+w'}{\frac{w}{c}+\frac{w'}{c'}}$$

$$= \frac{(w+w')\,c\,c'}{w\,c'+w'\,c}$$

CHAP. IX.

HYDRAULICS.

VELOCITY OF EFFLUX FROM AN APERTURE IN A VESSEL, — PROPORTIONAL TO THE DEPTH OF THE APERTURE, — EQUAL TO THE VELOCITY ACQUIRED IN FALLING THROUGH THAT DEPTH. — EFFECT OF ATMOSPHERIC RESISTANCE. — VENA CONTRACTA. — RATE AT WHICH THE LEVEL OF THE WATER IN THE VESSEL FALLS. — LATERAL COMMUNICATION OF MOTION BY A LIQUID. — RIVER FLOWING THROUGH A LAKE. — CURRENTS AND EDDIES. — EFFECTS OF THE SHAPE OF THE BED AND BANKS OF A RIVER. — FORCE OF A LIQUID STRIKING A SOLID, OR VICE VERSÂ. — EFFECT OF AN OAR. — WINGS OF A BIRD. — DIRECTION OF THE RESISTING SURFACE. — EFFECT OF THE VELOCITY OF THE STRIKING BODY. — SOLID OF LEAST RESISTANCE. — SHAPE OF FISHES AND BIRDS. — SPEED OF BOATS AND SHIPS LIMITED. — COMPARATIVE ADVANTAGES OF RAIL-ROADS AND CANALS.

(99.) We have hitherto confined our attention chiefly to those effects which are produced by the pressure transmitted by liquids, either arising from their own weight or from other forces applied to them, when confined within certain limits. When any of the limits or boundaries which confine a liquid are removed, the force which before was expended in exciting pressure on such boundary or limit will now put the liquid in motion, and cause it to escape through the space from which the opposing limit has been removed. The phenomena exhibited under such circumstances, form the subject of a branch of the mechanical theory of liquids usually called hydraulics. It embraces, therefore, the effects attending liquids issuing from orifices made in the reservoir which contain them; water forced by pressure in any direction through tubes or apertures, so as to form ornamental jets; the motion of liquids through pipes and in channels; the motion of rivers and canals; and the resistance produced by the mutual impact of liquids and solids in motion.

It is the peculiarity of this branch of hydrostatics, that, from various causes, the phenomena actually exhibited in nature or in the processes of art deviate so considerably from the results of theory, that the latter are of comparatively little use to the practical engineer. They also lose a great part of their charm for the general reader, from the impossibility of producing from the familiar objects, whether of nature or art, examples appositely and strikingly illustrative of the general truths derived from scientific reasoning. It must not, however, be supposed that the results of such investigations are false, or that the science itself, or the instruments by which it proceeds, are defective. The difficulty here lies rather in the peculiar nature of the phenomena, and the number of disturbing causes which render them incapable of that accurate classification and generalisation which is so successfully applied in almost every other department of physical science.

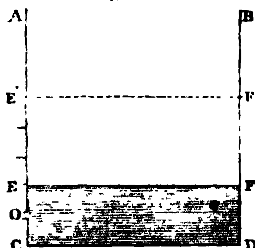
The only really useful method of treating a branch of knowledge so circumstanced, is to accompany a very concise account of such general principles as are least inapplicable to practice, by proportionately copious details of the most accurate experiments which have been instituted, with a view to ascertain the actual circumstances of the various phenomena. Such details, however, would be wholly misplaced in the present treatise; we shall, therefore, confine ourselves to a few observations on some of the most important and striking phenomena of hydraulics; tracing their connection, where it is possible, with the various analogous effects in the other parts of the mechanics of solids and fluids.

(100.) If a small hole be made in the side of a vessel which is filled with a liquid, the liquid will issue from it with a certain velocity. The force which thus puts the liquid in motion is that which, before the orifice was made, excited a pressure on the surface of the matter which stopped the orifice. It is obvious, that the moving force of the water which thus issues from the orifice must be adequate and proportional to the power which

produces it. But this power, being the same which produced the pressure upon the surface of the vessel, will be proportional to the depth of the orifice below the level of the liquid in the vessel (14.). Hence we may at once infer, that water will issue with more violence from an orifice at a greater depth below the surface than from one at a less depth; but it still remains to be determined what the exact proportion is between the rapidity of efflux and the depth of the orifice.

Let A B C D, *fig.* 65., be a vessel with perpendicular sides, having a very small orifice O near the bottom. Let it be filled with water to a certain height E F

Fig. 65.



above O. The pressure corresponding to the depth O E will cause the water to flow from O with a certain velocity. Suppose this velocity to be 10 feet in a second; and suppose that by this means a gallon of water is discharged from O in one minute, water being in the mean while supplied to the vessel in such a quantity as to maintain the level of the water in the vessel at E F. The pressure at O being therefore always the same, the velocity of efflux will be uniform. It is clear, that if water be now poured into the vessel, so as to fill it to a level higher than E F, the pressure at O being increased, the velocity of efflux at O will be also increased. Let it be required to determine how much higher than E F it will be necessary to fill the vessel, in order that the velocity with which the water is discharged at O shall be double the former velocity. The momentum or moving

force communicated to the water discharged from the orifice in one minute would in this case be four times that which was communicated to it in the former case; for, since the rapidity with which the water is discharged, is double its former velocity, double the quantity of water will be put in motion in one minute; but this double quantity is also moved with a double speed; hence the entire moving force produced in a minute will be four times the moving force produced in the former case in the same time. If the same quantity of water only had been put in motion with a double velocity, the moving force would be doubled; but the quantity of water moved being doubled as well as its speed, the moving force is quadrupled. Hence it follows, that the power which produces this effect must have four times the energy of that which produced the effect in the first case; but this power is the pressure produced at the orifice O, which is proportional to the depth of O below the surface. Hence it follows that to give a double velocity of discharge a fourfold depth is necessary. If the vessel A B C D be filled to the level E′F′, so that E′O shall be four times E O, then the velocity of discharge at O will be double the velocity when the level was at E F.

By similar reasoning in may be concluded that, to obtain a threefold velocity, a ninefold depth is necessary; for a fourfold velocity, sixteen times the depth will be required, and so on: in fact, in whatever proportion the velocity of efflux is increased, the quantity of liquid discharged in a given time must be also increased; and, therefore, the pressure or the depth must not only be increased in proportion to the velocity, but also as many times more in proportion to the quantity discharged. Thus the depth of the orifice, below the surface, will always be in proportion to what, in mathematics, is called the square of the velocity of discharge.

If in a vessel A B C D, *fig.* 66., filled with a liquid, a small hole, O, be made at one inch below the surface E F; and another, O′, at 4 inches below it; a third, O″, at 9 inches; a fourth, O‴, at 16 inches; and a fifth, O⁗,

at 25 inches; the velocities of discharge at these several holes will be in the proportion of 1, 2, 3, 4, and 5. If

Fig. 66.

A B

D

the upper line in the following table express the several velocities of discharge, the lower one will express the corresponding depths of the orifices :—

Velocity.	1	2	3	4	5	6	7	8	9	10
Depth.	1	4	9	16	25	36	49	64	81	100

It is impossible to contemplate the relation exhibited in this table without being struck by the remarkable coincidence which it exhibits with the relation between the height from which a body falls and the velocity acquired at the end of the fall.* To produce a twofold velocity, a fourfold height is necessary. To produce a threefold velocity, a ninefold height is required. For a fourfold velocity, a sixteenfold height is required, and so on. Thus it appears, that if a body were allowed to fall from the surface F of the water in the vessel downwards towards C, and unobstructed by the fluid, it would, on arriving at each of the orifices above described,

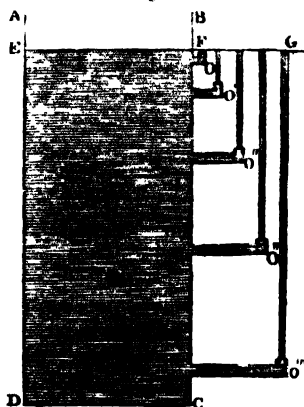
* Cab Cyc. Mechanics, p. 88.

have velocities proportional to those of the water discharged at the orifices respectively. Thus, whatever velocity it would have acquired on arriving at O, the first orifice, it would have double that velocity on arriving at O′, the second orifice, three times that velocity on arriving at the third O″, and so on. Now, it is evident that if the velocity of efflux at any one of the orifices be equal to the velocity acquired by the body in falling from the surface F to that orifice, then the velocities acquired at each of the orifices will be equal to the velocities of discharge respectively. Thus, if the velocity acquired in falling from F to O be equal to the velocity of discharge at O, then the velocity acquired in falling from F to O′ being double the former, will be equal to the velocity of discharge at O′; and in like manner the velocity acquired at O″ being three times the velocity at O, will be equal to the velocity of discharge at O″. In order, therefore, to establish the remarkable fact that the velocity with which a liquid spouts from an orifice in a vessel is equal to the velocity which a body would acquire in falling unobstructed from the surface of the liquid to the depth of the orifice, it is only necessary to prove the truth of this principle in any one particular case. Now it is manifestly true, if the orifice be presented downwards, and the column of fluid over it be of very small height; for then this indefinitely small column will drop out of the orifice by the mere effect of its own weight, and therefore with the same velocity as any other falling body; but as fluids transmit pressure equally in all directions, the same effect will be produced whatever be the direction of the orifice. Hence it is plain that the principle just expressed is true when the depth of the orifice below the surface is indefinitely small; and since it is true in this case, it must, according to what has been already explained, be also true in every other.

(101.) From this theorem it follows, as a necessary consequence, that if the orifices from which the liquid is discharged be presented upwards, the jets of liquid which would escape from them would rise to a height equal to

the level of the liquid in the vessel. Thus, in *fig.* 67., if E F be the surface of the liquid, and O, O', O'', O''', be four orifices at different depths, all opening directly upwards, the liquid will spout from each of them with the velocity which a body would acquire in falling from the level of the surface E F G to the orifices respectively,

Fig. 67.



and consequently the liquid must rise to the same height before it loses the velocity with which it was discharged. Hence the jets severally issuing from the orifices will rise to the height F G.

(102.) These important theorems must, however, be submitted to considerable modifications before they can be considered as applicable in practice. In the preceding investigation, we have considered the orifice to be indefinitely small, so that every point of it may be regarded as at the same depth below the surface; we have also considered that the fluid in escaping from the orifice is subject to no resistance from friction or other causes; and also that in its ascent in jets it is free from atmospheric resistance. In practice, however, all these causes produce very sensible effects, and the consequence is, that

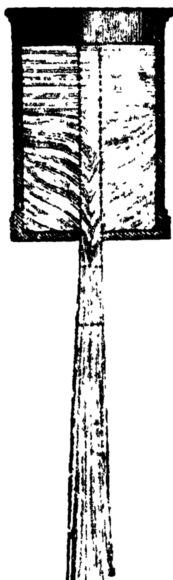
the actual phenomena vary very considerably from the results of theory. The velocity of efflux is, from the moment the orifice is opened, diminished by the friction of the liquid against the sides of the pipe or opening through which it passes. After it escapes, the resistance of the air produces a sensible effect upon the movement of the fluid particles. This resistance increases even more rapidly than the velocity, so that the jets which escape from the lower orifices are still more resisted in proportion than those from the higher, and consequently they do not rise even near the level of the fluid in the vessel.

As the liquid is gradually discharged from the orifice. the contents of the vessel descend, the various particles falling in lines nearly perpendicular; but when they approach near the orifice from which they are to escape, they begin to change their direction, and to tend toward the orifice, so that their motion is in lines, converging towards the opening, and meeting at a point outside it. These effects will be produced whether the opening be in the bottom or in the side of the vessel. They may be rendered visible by using a glass vessel filled with water, in which filings or small fragments of solid substances are suspended, and which are carried along by the motion of the currents.

If a vessel be allowed to empty itself by an orifice in the bottom, the surface of the liquid will gradually descend, maintaining its horizontal position; but, when it comes within a small distance, about half an inch, of the bottom, a slight depression or hollow will be observed in that part of the surface which is immediately over the orifice. This will increase until it assume the shape of a cone or funnel, the centre or lowest point of which will be in the orifice, and the liquid will be observed flowing in lines directed to this centre. This effect will be better understood by referring to *fig.* 68., where the direction of the currents and the contracted vein are exhibited.

As the particles of liquid in approaching the orifice move in directions converging to a point outside it, it is

Fig. 68.



plain that the column of fluid which escapes from the vessel will be narrower or more contracted at the point towards which the motion of the liquid converges than it is either before it arrives at that point or after it has passed it. This contraction of the jet produced by the peculiar directions which the motions of the fluid particles take was first noticed by Newton, who gave it the name of the *vena contracta* or the *contracted vein* of fluid. The distance from the orifice at which the greatest contraction of the jet takes place depends, with certain limitations, on the magnitude of the orifice. If the orifice be circular and small, its distance is equal to half the diameter of the orifice, and the magnitude of the jet at its most contracted point bears to the magnitude of the orifice, according to Newton, the proportion of 1000 to 1414, and according to Bossut, the proportion of 1000 to 1600.

It will be evident, upon very slight consideration, that if the liquid be suffered to escape by a cylindrical tube, the contraction of the vein will be greatly diminished. In this case the proportion of the magnitude of the most contracted part to that of the bore of the tube is 1000 to 1200.

As the same quantity of fluid which passes in any given time through the orifice must pass in the same time through the narrower space of the contracted vein, it follows, that it must pass through this place with a proportionally greater velocity. Its velocity, therefore, at the point called the contracted vein, is greater than at the orifice in the proportion 1414 to 1000, according to Newton's calculation.

In applying the theorem which has been established respecting the equality of the velocity of efflux to that

of a body which has fallen from the surface to the orifice, it is the velocity of the contracted vein which should be regarded, that being the point at which the pressure produces its greatest effects.

(103.) In the preceding investigation we have supposed liquid to be supplied to the vessel as fast as it is discharged, so that the surface is maintained at the same height above the orifice. The pressure is therefore constant, and the velocity of efflux uniform. But if a vessel discharge its contents by an orifice in the lower part, then the surface will continually descend. The pressure at the orifice will be continually diminished, and the square of the velocity of discharge, which is proportional to this pressure, will suffer a corresponding diminution. Hence it appears that the velocity of discharge is continually less until the surface falls to the level of the orifice.

It is not difficult to perceive, that an invariable proportion must subsist between the velocity of discharge and the velocity with which the surface of the liquid in the vessels falls. Suppose that the magnitude of the orifice is the hundredth part of the magnitude of the surface of the liquid, and that the rate of discharge at any moment is such that a cubic inch of the liquid would be discharged in one second: in that time a column of the liquid will pass through the orifice, whose base is equal to the orifice, and whose height is such that its entire magnitude will be a cubic inch. In the same time the level of the liquid in the vessel will fall through a space which would require a cubic inch of the liquid to fill. This space will be just as much less than the height of the former column, as the magnitude of the orifice is less than the magnitude of the surface of the liquid; that is, in the instance assumed, the space through which the surface will descend in one second will be the hundredth part of the space through which the liquid projected from the orifice would move in a second, if its velocity were continued uniform.

By the same reasoning, it may be inferred generally, that the velocity with which the surface descends bears

to the velocity of discharge the same ratio as the magnitude of the orifice bears to the magnitude of the surface.

Since it has been already proved that the square of the velocity of discharge is proportional to the depth of the orifice, it follows, from what has been just stated, that the square of the velocity with which the surface descends is also proportional to the depth of the orifice. It is proved in mechanics, that when a body is projected upwards, commencing with a certain velocity, the square of its velocity diminishes in proportion to its distance from its point of greatest elevation. It therefore follows, that such a body is retarded as it approaches its greatest height, according to the same law as the velocity of the surface of a liquid in descending is retarded as it approaches the orifice at which it is discharged.

Thus all the properties established in mechanics respecting bodies projected upwards and retarded by the force of gravity, may be applied to the descent of the surface of a vessel which is emptied by an aperture in any part below that surface. The initial velocity of the surface is easily found. The velocity of efflux at the orifice is that which would be acquired by a body falling from the surface to the orifice and may be determined by the ordinary principles of mechanics.* This velocity, being diminished in the proportion of the magnitude of the surface of the liquid to the magnitude of the orifice, will give the initial velocity of the surface in its descent. The velocity at any other elevation may be calculated upon the principle that the squares of the velocities at any two elevations above the orifice are proportional to these elevations.

It is proved in mechanics, that if a body be projected upwards with a certain velocity, the height to which it will rise will be equal to half the space through which it would move in the same time with the velocity of projection continued uniform. Hence, by analogy, we infer, that the time which the surface of a liquid takes to fall from any given elevation to the orifice is equal to

* Cab. Cyc. Mechanics, chap. vii.

the time it would take to move through twice that elevation with the initial velocity continued uniform. Now as this initial velocity is known. the time which the surface would take to move through twice the elevation with it may be computed; and, therefore, the time which the surface takes to move from any given elevation to the orifice will be obtained.

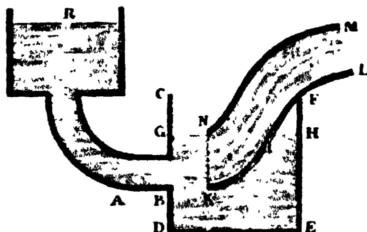
Hence it is easy to infer, that the time in which a vessel will empty itself through a hole in the bottom is equal to the time it would take to discharge twice the quantity of fluid contained in the vessel, if the initial velocity were continued uniform.

(104.) If a stream of liquid be impelled through a reservoir, in which the liquid is at rest, it is evident that it will drive before it those parts of the liquid which impede its course; but, independently of this, it will produce other motions in those parts of the liquid in the reservoir near which it passes. Let us suppose a river to enter an extended lake at one extremity, and to issue from it at the other; the bed of the river being more shallow and contracted than the lake. If a hollow channel or aqueduct were formed across the lake, equal in magnitude and shape with the bed of the river, the water of the river would flow across the lake without producing any effect upon the waters of the lake, being separated from them by the channel or aqueduct which we have supposed. If the surface of the river, flowing in the channel, coincide with the level of the surface of the lake, the channel or aqueduct will sustain no pressure or strain, or, more properly, the pressures which it will suffer on all sides will be equal; the waters of the lake pressing it upwards and inwards, with forces exactly equal to those by which the waters of the river press it downwards and outwards. It is clear, therefore, that the channel has no effect in sustaining or neutralising any hydrostatical pressure, and that its removal will not call into action any force of this kind. Suppose it then removed, and the waters of the lake themselves to form the channel through which the waters of the river flow.

Shall we conclude, that in this case the waters of the river will continue to flow through those of the lake, the latter remaining quiescent, and the two masses of liquid being unmingled? It has been found by experiment that such will not be the effect. The current of the river flowing in contact with the waters of the lake will impart to them a share of its own motion; and these again will communicate the motion to those beyond them, until at length the waters of the lake, to a great extent, on each side of the course of the river, are put in motion.

The following experiment was instituted by Venturi to illustrate the principle of the lateral propagation of motion by a liquid. A horizontal pipe A B, *fig.* 69.,

Fig. 69.



was introduced into a vessel C D E F, which was previously filled with water to the level G H. Opposite to the mouth of A B, and at a short distance from it, was placed a small rectangular canal K L M N of thin metal, with a curved bottom, perpendicular sides, and open at the top. This canal was so placed as to be capable of conducting a stream, flowing in at N K, over the edge of the vessel F; and discharging it at M L. The pipe A B communicates with a reservoir R, kept constantly filled to the same height, so that the water issues from B continually, with the same rapidity. The current flowing from B passes through the water in the reservoir C D E F, in the space between B and K, and enters the curved canal K L: it is forced up this by the

velocity with which it issues from B, and flows out at L. By this arrangement, a current, equal in magnitude to the pipe A B, is continually flowing through the water in the reservoir C D E F, in the space between B and N K.

The effect of this has been found by experiment to be, that the whole of the liquid in the vessel C D E F, which is above the level B K, is carried with the liquid which passes from the tube A B, up the canal K L, and discharged at L. The surface G H gradually falls, and is soon reduced to the level B K, where it remains.

The lateral communication of motion by fluids, here described, is not confined to the case where the fluid to which the motion is imparted, is of the same kind as that from which the motion is received. A current of water passing through the air will give to the air immediately contiguous to it a motion in the same direction. If a feather, or any other light body, be suspended by a long fine silken thread, and held immediately over the surface of a rapid stream, but not in contact with it, it will be found to be driven along in the direction of the stream, in the same manner as it would happen were it exposed to a blast of air. This effect, as might naturally be expected, is greatly increased when the velocity of the stream is very considerable. A cascade, which falls from a great elevation, produces a current of air, the force of which can scarcely be withstood. Venturi, who investigated and explained this phenomenon, observed a remarkable example of it, in a waterfall, which descends from the glacier of Roche Melon, on the rock of La Novalese, near Mount Cenis.

The lateral communication of motion, combined with the irregularities in the shape of beds and banks of rivers, is the cause which produces eddies of water, which are frequently observed in them.

Let *fig.* 70. represent the surface of a river, N R and O S being the shape of its banks; suppose the current to run in the direction N R, and let B A be an obstacle projecting from one of the banks and impeding its

course: the water will thus be caused to rise higher above B A, and to discharge itself round the point A with increased velocity. The liquid in the space B D C A being protected from the force of the descending stream by the obstacle B A, will at first be quiescent; but the rapid flow of the water from the point A will communicate motion to the lateral particles in the space C, and

Fig. 70.



will convey them forward. The particles at E will then become slightly depressed, and the remoter particles towards D will have a tendency to fill the depression; the current from A to C will, however, continue to carry them off, and a hollow will continue in the centre of the space A C D. The water between A and C is thus acted upon by two forces; viz. the force communicated to it laterally, and tending to carry it down the stream in the direction A C, and the tendency which it has by its gravity to fall towards the centre of the cavity E. These two forces are precisely analogous to those by which a body is caused to move in a circular orbit, viz. a projectile force at right angles to the radius of the circle, and an attractive force continually soliciting the body to the centre. The water by this means is whirled round in an eddy, which is continually maintained by the action of the stream in rushing from the point A.

A sudden contraction of the bed of the river, followed immediately by a widening of the banks, as at N O P Q, will produce the same effect as two obstacles, such as B A, placed on opposite sides of the river; consequently, under such circumstances, eddies will be observed on both sides at P and Q immediately after passing the contraction.

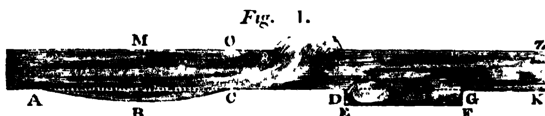
The stream of water shooting from A will strike the opposite bank at G H, and will be reflected from it in

the direction H S; the effect will, therefore, be the same at H as if the current encountered an obstacle there similar to B A, and, consequently, eddies will be repeated in the space near R. It follows, therefore, that a sudden contraction of the banks succeeded by a widening will not only produce eddies immediately adjacent to the contraction, but that these eddies will be continued for a certain space afterwards.

Similar effects may be expected by inequalities in the bottom of a river; but, instead of taking place as just described, in a direction parallel to the surface, they will be produced in a plane perpendicular to it, and the eddies will be presented upwards like the curling on the crest of a wave.

Let *fig.* 71. represent the section of a river perpen-

Fig. 1.



dicular to its surface, A K exhibiting the shape of the bottom. In the case of a gentle slope, such as A B C, let us first suppose the space A B C to be filled with water, which is quiescent, the stream of the river running upon its surface A C; the motion of the river will be gradually communicated to the water below A C, so as to give it a motion from A towards C. The shape of the bottom A B C will cause it to be projected from C towards the surface, forming a vertical eddy which will frequently terminate in a curling wave. In this case B C acts in the same manner upwards as B A, in *fig.* 70., did laterally. If the extremities of the hollow be abrupt as at D G, subaqueous eddies will be produced.

All these effects may be exhibited experimentally, by causing water to flow through artificial channels with glass sides.

It will be evident from all that has been stated, that irregularities in the bottom and sides of rivers must necessarily retard their currents; the force which would

otherwise carry the stream directly down its channel is here wasted in producing lateral and oblique motions. All the moving force of the water in an eddy must be originally derived from the precipitous descent of the stream, which is therefore robbed of all the power requisite for the maintenance of such effects. We, therefore, perceive why the velocity of rivers, in their descent to the ocean, is always much less than that which would be calculated upon mechanical principles, supposing them to flow in a perfectly even and regular channel. In fact, the effects of such inequalities partake, in a certain degree, of the nature of friction; they are, as it were, friction on a large scale. It is also evident why rivers, the beds of which descend towards the sea with equal acclivities, yet may have very different velocities, the velocity being greater the more regular the channel.

(105.) When a liquid in motion strikes a solid surface at rest, or when a solid surface in motion strikes a liquid at rest, the quiescent body deprives the moving one of a quantity of force equal to that which it receives *; and this loss of force is said to arise from the resistance which the quiescent body offers to the body in motion. When a solid body is immersed in a liquid, the force necessary to move it with any given velocity is found to be greater than that which would be necessary to move it with the same velocity when not immersed: this excess of force arises from the resistance of the liquid to the solid, and it is a problem of great practical importance to establish the rules or theorems by which this resistance may be estimated, and by which its laws may be exhibited. The same rules precisely will be applicable to solid bodies, such as the float boards of a water-wheel when struck by the water of a mill course. In the one case the force to be measured is called the resistance of the liquid, and in the other it is denominated the percussion of the liquid. In these, as in almost every other part of hydraulics, theory lends but feeble aid to practice. There are many effects attending

* Cab. Cyc. Mechanics, chap. iv.

the operation of the liquid, whether in resisting or communicating motion, which, from their nature, elude the grasp of theory, and appear to be incapable of being represented by mathematical or arithmetical language or symbols: nevertheless, there are a few general principles which may be regarded as approximating within a certain degree of practical results, and sufficiently near them to impress upon the memory a general notion of the phenomena, if not to be useful in the actual calculations of the engineer.

Indeed, the first steps in generalising this class of effects are almost as obvious to the most common experience as their exact determination is difficult. For example, if a flat board of a foot square be moved in water with a certain velocity, so that its flat side shall be presented in the direction of its motion, a certain resistance is felt, and a certain force is necessary to keep it in motion; but if the same board be moved in the direction of its edge, it is well known that a much less force will be found necessary to give it the same velocity as in the former case. When the boatman plies his oar, he keeps the flat part of the blade presented in the direction in which he pulls at that part of the stroke at which the greatest effect is produced in impelling the boat; but when he wishes to extricate the oar from the liquid, preparatory to another impulse, he turns the blade edgeways towards the water, and the resistance, which before was powerful, becomes immediately insignificant. When the wings of a bird are spread for flight, the flat and broad part of their plumage is presented downwards, to give them support from the resistance of the air in that direction, while their edge is presented forwards, to enable them to cleave the air with as little resistance as possible in that direction.

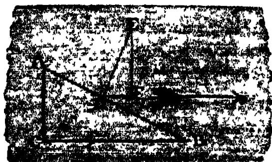
These and like effects, which constantly fall under our observation, indicate the general fact, that the broader the surface presented in the direction of the motion, the greater will be the resistance. But it requires more accurate and philosophic examination, to decide whether

the increase of resistance be always in the exact proportion of the increase of surface presented towards the motion: both theory and experience decide this question in the affirmative. The resistance arises from the force which the moving body must expend in displacing the particles of fluid which lie in its way: all other things being the same, this force must obviously be proportional to the number of particles to be displaced; this number will evidently be determined by the magnitude of the surface. A flat board of the magnitude of one square foot displaces a certain quantity of liquid by its motion; one of two square feet will displace twice that quantity; and, therefore, will require twice the force to keep it in motion; or, in other words, will suffer twice the resistance; and the same will be true whatever be the magnitude of the surface. We, therefore, conclude generally that—

"When a flat surface is moved perpendicularly against a fluid, the resistance which it suffers will increase or decrease in the same proportion as the magnitude of the surface is increased or decreased."

(106.) If, instead of being presented perpendicularly to the liquid, the surface be presented obliquely with respect to the direction of its motion, the resistance will be diminished on two accounts: first, The quantity of liquid displaced will be less; and, secondly, The action of the surface in displacing it will have the mechanical advantage of an inclined plane, or wedge, so that instead of driving the liquid forward, it will in some measure push it aside.

Fig. 72.



Let A B, *fig.* 72., be the surface of a solid moving in

a liquid in the direction expressed by the arrow. It is evident that the quantity of liquid displaced by the surface A B is the same as that which would be displaced by the smaller surface A C moving perpendicularly against the liquid. Let us suppose that A C is half the magnitude of A B; it follows, therefore, that the quantity of liquid which would be displaced by A C is half that which would be displaced by A B, if it move perpendicularly against the liquid. Hence, it may be inferred, that by reason of the oblique position of A B, the quantity of liquid which it displaces is reduced one half.

Again, this reduced quantity of liquid which is so displaced, is not driven perpendicularly before the moving surface. The surface A B acts on each particle of the liquid as a wedge acts in cleaving a piece of timber; and, by the principles of mechanics, it is established that a power acting against A C will overcome a force on the face of the wedge greater than its own amount in the proportion of A B to A C *; or, in the case already supposed, that of two to one. We, therefore, conclude, that in the oblique position of the surface A B, compared with the same surface moving perpendicularly against the liquid, only half the quantity of liquid is displaced, and that quantity only offers half the resistance which the same quantity would offer to perpendicular motion of the surface A B. The conclusion is, that by the obliquity of the surface A B the resistance is reduced to one fourth of its amount.

In like manner, if A C were a third of A B, the resistance would be reduced to one ninth of its amount. If A C were a fourth of A B, the resistance would be reduced to a sixteenth of its amount, and so on; the resistance being always diminished in the proportion of the square of the back of the wedge, as compared with its face.

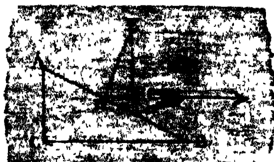
In trigonometry, the number which expresses the proportion of A C to A B is called the sine of the angle at B; and thus the resistance to a surface moving in a

* Cab. Cyc Mechanics, chap. xvi.

liquid is said to increase or decrease in proportion to the square of the sine of the angle which the direction of the surface makes with the direction in which it is moved.

The resistance here determined is that which acts perpendicularly on the surface A B. The portion of it

Fig. 72.



which acts in the direction of the motion may be found by the principles for the resolution of force. Let D E express the resistance perpendicular to A B, and let E F be drawn perpendicular to the direction of the motion, D F will express that part of the resistance which acts against the motion. The proportion of D F to D E is the same as that of A C to A B.*

(107.) We have hitherto omitted the consideration of the effect produced upon the resistance of the fluid by any change in the velocity with which it strikes the solid, or with which the solid strikes it. If a flat board be moved perpendicularly against a liquid, it is quite evident that the greater the velocity with which it is moved, the greater will be the resistance which the liquid will offer to it; and this effect may in part be accounted for very obviously. It has been already explained, that the resistance arises from the force which the solid loses in giving motion to the liquid which stands in its way. It is clear that the more rapid the motion of the solid is, the greater will be the velocity which it will communicate to the fluid, and, therefore, the greater the force with which the fluid will be propelled; and, by consequence, the greater will be the resistance opposed to the solid. But the increase of resistance is not merely in proportion

* Cab. Cyc. Mechanics, chap. v.

to the velocity. Each particle of the fluid which the solid strikes during one second of time if it moves with a double speed, receives from it a double force, and therefore offers to it a double resistance. But, besides this, the circumstance of the body moving with a double speed causes it to strike twice as many particles in a second; each particle, as just stated, being struck with a double force. It is, therefore, apparent that a double speed will cause the body to impart a fourfold force to the liquid which it puts in motion. It will put double the quantity of liquid in motion with a double velocity; it follows, therefore, that it will be opposed by a fourfold resistance.

By like reasoning, it will be easy to prove that a threefold velocity will produce a ninefold resistance; that a fourfold velocity will cause the resistance to be increased sixteen times, and so on; the resistance varying in proportion to the square of the velocity.

(108.) In the preceding investigation we have explained how the quantity of resistance is varied by any change in the magnitude or figure of the solid, or in the velocity with which it is moved. But, in order to render these conclusions useful, it will be necessary to show the actual amount of the resistance in some one particular case. If this be known, its amount in all other cases may be calculated by the theorems just explained. Thus, if the absolute resistance produced by any particular velocity be known, the resistance which would be produced by any other velocity may be computed from the established principle, that the resistance varies in proportion to the square of the velocity.

Experiments were instituted by Bossut, with a view to determine the absolute resistance sustained by a solid moved in a liquid. By these experiments it was found that if a flat board were moved perpendicularly against a liquid, it would suffer a resistance equal to the weight of a column of the fluid, the base of which is equal to the board, and the height of which is equal to the height from which a body should fall, in order to ac-

quire the velocity with which the board is moved against the liquid.

It follows from this, that the resistance of different fluids will be different according to their specific gravities, for the heavier a column of the same height is, the greater in the same proportion will the resistance be. Thus the resistance of sea water is greater, in a slight degree, than that of fresh water; and the resistance of mercury is many times greater than either.

When a jet of liquid strikes a solid at rest, it is found that the absolute resistance is different, but that its variation depends upon the same laws. In this case the force sustained by the solid is equal to the weight of a column of the liquid, whose height is double the height from which a body should fall to acquire the velocity. Hence it follows, that a vein of liquid striking a solid with a certain velocity produces an effect amounting to double that which would be produced by moving the solid with the same velocity in a similar liquid at rest.

(109.) The theorems just established constitute the only results in hydraulics which deserve the name of general principles, and which approximate within a limit sufficiently close to the actual phenomena to be of any practical utility. But even in the application of these there are several circumstances which ought to be taken into consideration, in restricting and modifying the conclusions deduced from them. They are, however, attended with several consequences which experience fully verifies, and which are of considerable importance in the practical applications of the science.

The effect produced on the resistance of a liquid by the obliquity of the surface of the solid which moves through it forms a prominent element in the problem for determining, under different conditions, the shape of the solid. This consideration must materially affect the shape to be given to vessels of all denominations, whether for navigating the seas, or for inland transport by canals and rivers. It is this principle which causes the length of the vessel to be presented in the direction of

the motion, and which gives a sharp prow, where circumstances admit it, the advantage over a round one. The boats which ply on rivers, or other sheets of water not liable to much agitation, nor intended to carry considerable freight, are so constructed, that every part of their bottom which encounters the liquid moves against it at an extremely oblique angle. The boats for the conveyance of persons to short distances on the Thames, and other rivers, afford obvious examples of this.

Art in these cases only imitates nature. Animals, to whose existence or enjoyment a power of easy and rapid motion in fluids is necessary, have been created in a form which, with a due regard to their other functions, is the best adapted for this end. Birds, and especially those of rapid flight, are examples of this. The neck and breast tapering from before, and increasing by slow degrees towards the thicker part of the body, cause them to encounter the air with a degree of obliquity greatly diminishing the resistance, slight as it is, which that attenuated fluid opposes to their flight; but we find a more striking illustration of the same principle in the forms of fishes of every denomination. The reader must not, however, be tempted to indulge in the supposition that nature has in these cases solved the celebrated problem, to find the form of the solid of least resistance. The solid contemplated in that problem has no other function to discharge except to oppose the resistance of the fluid, and the question is one of a purely abstract nature, viz. what shape shall be given to a body so that while its volume and surface continue to be of the same magnitude, it will suffer the least possible resistance in moving through a fluid? It will be apparent that many conditions must enter into the construction of an animal, corresponding to its various properties and functions, independently of those in virtue of which it impels itself through the deep, or cleaves the air. The detection of verifications of the results of theory in the works of nature is in general so seductive, that writers are sometimes tempted to overlook the in-

evitable causes of discrepancy in their eagerness to seize upon analogies of this kind. Without, however, seeking in natural objects the exact solution of a mathematical problem unencumbered by various conditions which nature has to fulfil, the examples which have been produced give abundant manifestation of design in the works of the Creator, which is, or ought to be, the chief source of the delight which attends such illustrations.

(110.) The resistance arising from the quantity of fluid displaced by the moving body may, therefore, be always greatly diminished, and in some cases rendered almost insignificant by a proper adaptation of its shape. The accumulated resistance arising from the increased speed of motion is, however, an impediment which no art can remove. The fact that the resistance of a liquid to a body moving in it increases in a prodigiously rapid proportion in respect of the increase of velocity, is one which sets an impassable limit to the expedition of transport by vessels moving on the surface of water. This property has long been well known; but it has received greatly increased importance from the recent improvements in the application of steam. If a certain power be required to impel a vessel at the rate of five miles an hour, it might at first view be thought that double that power would cause it to move at the rate of ten miles an hour; but, from what has been already proved, it will be perceived that four times the power is necessary to produce this effect. In like manner, to cause the vessel to move at the rate of fifteen miles an hour, or to give it three times its original speed, nine times the original power is necessary. Thus it follows, that the expenditure of the moving principle, whether it be the power of a steam engine or the strength of animals, increases in a much larger ratio than the increase of useful effect. If a boat on a canal be carried three miles an hour by the strength of two horses, to carry it six miles an hour would require four times that number, or eight horses. Thus double the work would be executed at four times the expense.

(111.) These considerations place in a conspicuous point of view the advantages which transport by steam engines on rail roads possesses over the means of carriage furnished by inland navigation. The moving power has in each case to overcome the inertia of the load; but the resistance on the road, instead of increasing as in the canal in a faster proportion than the velocity, does not increase at all. The friction of a carriage on a rail road moving sixty miles an hour would not be greater than if it moved but one mile an hour, while the resistance in a river or canal, were such a motion possible, would be multiplied 3600 times. In propelling a carriage on a level rail road the expenditure of power will not be in a greater ratio than that of the increase of speed, and therefore the cost will maintain a proportion with the useful effect, whereas in moving a boat on a canal or river every increase of speed, or of useful effect, entails an enormously increased consumption of the moving principle.

But we have here supposed that the same means may be resorted to for propelling boats on a canal, and carriages on a rail road. It does not, however, appear hitherto that this is practicable. Impediments to the use of steam on canals have hitherto, except in rare instances, impeded its application on them; and we are forced to resort to animal power to propel the boats. We have here another immense disadvantage to encounter. The expenditure of animal strength takes place in a far greater proportion than the increase of speed. Thus, if a horse of a certain strength is barely able to transport a given load ten miles a day for a continuance, two horses of the same strength will be altogether insufficient to transport the same load twenty miles a-day. To accomplish that a much greater number of similar horses would be requisite. If a still greater speed be attempted, the number of horses necessary to accomplish it would be increased in a prodigiously rapid proportion. This will be evident if the extreme case be considered, viz.

that there is a limit of speed which the horses under no circumstances can exceed.*

The astonishment which has been excited in the public mind, by the extraordinary results recently exhibited in propelling heavy carriages by steam engines on rail roads, will subside if these circumstances be duly considered. The moving power and the resistance are naturally compared with other moving powers and resistances to which our minds have been familiar. To the power of a steam engine there is, in fact, no practical limit; the size of the machine and the strength of the materials excepted. This is compared with agents to whose powers nature has not only imposed a limit but a narrow one. The strength of animals is circumscribed, and their power of speed still more so. Again, the resistance arising from friction on a road may be diminished by art without any assignable limit, nor does it sustain the least increase to whatever extent the speed of the motion may be augmented; on the contrary, the motion of a vessel through a canal has to encounter a resistance by increase of speed, which soon attains an amount which would defy even the force of steam itself were it applicable to overcome it with any useful effect.

* Cab Cyc. Mechanics, chap. xx.

CHAP. X.

OF HYDRAULIC MACHINES.

WATER-WHEELS.—OVERSHOT.—UNDERSHOT.—BREAST.—BARKER'S MILL.—ARCHIMEDES' SCREW.—SLUICE GOVERNOR.—CHAIN PUMP.

(112.) The term "hydraulic machinery," in its general sense, is understood to comprise all machines in which the force of water is used as a prime mover, and also those in which other powers are applied for the purpose of raising or impelling water itself. Many of these machines, however, owe their efficacy to principles and properties, the investigation of which properly belongs to departments of physical science foreign to that which forms the subject of the present treatise. We shall, therefore, here confine our observations to such machines, or parts of machines, as admit of explanation by the principles of hydrostatical science, combined with the ordinary principles of mechanics.

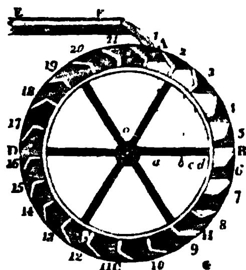
(113.) The most usual way in which water is applied as a prime mover to machinery, is by causing it to act either by its impulse in motion, or by its weight on the circumference of a wheel, in a direction at right angles, to the spokes or radii, and thus to make the wheel revolve and communicate motion to its axis. This motion is transmitted in the usual way, by wheel-work and other contrivances, to the machinery which it is required to work.

Water wheels vary in their construction, according to the way in which the force of the liquid is intended to be applied to them. The principal forms which they assume are denominated overshot, undershot, and breast wheels.

Overshot Wheel.

(114.) The most common form of the overshot wheel is represented in *fig.* 73. On the rim of the wheel a number of cavities, called buckets, are constructed, which in the figure are exposed to view, by supposing one of the sides which enclose them to be removed. What may be called the mouths of the buckets are all presented in one direction in going round the wheel, and by this means the buckets on one side will always have their

Fig. 73.



mouths presented upwards or nearly so, while those on the other side will have their mouths presented downwards. It follows, therefore, that the buckets on the side B are in such a position that all of them are capable of containing some water, and some of them of being kept filled, while those on the side D are incapable of retaining any liquid. Let us suppose a stream to flow from F into the bucket marked 1. The weight of the water which fills this bucket will cause the wheel to turn in the direction 1 2 3, &c., and the other buckets will successively come under the stream, and become filled; and this continues until the range of buckets from A to B are filled. As the buckets approach B they begin slightly to lose the liquid by their change of position, and after passing B this loss is rapid, so that before they arrive at the lowest point C, they are empty, and in that state they ascend

round C D to A, where they are again replenished. It appears, therefore, that there is a weight of water continually acting on one side of the wheel, distributed in the buckets from 1 to 8, and that this weight is not neutralised by any corresponding weight on the opposite side. The wheel is, therefore, kept continually revolving in the direction A B C D. A reference to the properties of the lever, or the wheel and axle as explained in Mechanics *, will make it apparent that the water contained in the several buckets is not equally efficacious in giving motion to the wheel. The weight of the water which fills the bucket 1 has the same effect in turning the wheel as an equal weight acting downwards at *a* would have in turning the lever D B on the centre O. In like manner the weight of the water in bucket 2 has the same effect in turning the wheel, as a similar weight acting at *b* would have in turning the same lever D B. Now if the weights be the same, the efficacy to turn the lever will be increased in the proportion of O *a* to O *b*. Although the contents of the bucket in passing from 1 to 2 may experience a slight diminution, yet this loss is perfectly insignificant compared with the advantage of the increased leverage O *b*. In like manner the leverage continues to increase; that of the bucket 3 being O *c*, of 4 being O *d*, and, finally, the bucket 5 having the leverage of the whole radius. After passing below B the leverage begins, on the contrary, to decrease, and continues to decrease until it arrives at C. From these circumstances it is obvious that the efficacy of the wheel will, in a great degree, depend on giving the buckets such a form as will cause them to lose as little water as possible until they pass the point B, where they have the greatest mechanical advantage. As they approach C the circumstance of discharging their contents becomes of less importance because of the decreasing leverage.

Millwrights have expended much ingenuity in contriving forms for the buckets, calculated to retain the water in those parts of the circumference where its

* Cab. Cyc. Mechanics, chap. xiv.

action is most efficacious, and to discharge it with facility and expedition. Details on this subject would, however, be misplaced in the present treatise.

Numerous experiments have been made to determine the most advantageous size of overshot wheels, and the best velocity at which they can be worked. Most authors are of opinion, that the diameter of an overshot wheel should never exceed the height of the fall of water by which it is impelled; but that it should be as nearly equal to this as is consistent with giving the water sufficient velocity on entering the buckets. Some, however, think, that the diameter might with advantage even exceed the height of the fall. With respect to the velocity of the wheel, some maintain that the slower the motion the greater will be the effect; while others hold that there is a certain velocity (of very small amount) which will give a maximum effect, and assert that those who maintain the contrary opinion have not carried their experiments to a sufficient extent to establish the principle.

It requires little reflection to be able to perceive how the useful effect may be greatest when the wheel moves with a certain velocity, any increase or decrease of that velocity diminishing the actual quantity of work done in a given time. The power of the wheel being the same, the velocity with which it moves will be less in proportion as its load is increased. Suppose a water wheel works a flour mill, in which, at different times, it has to move a different number of millstones, it is evident that the greater the number it has to move, the slower will be the motion which it will impart to each; and, therefore, although the quantity of flour produced will be increased by increasing the number of stones, yet the quantity which each stone will produce will be diminished by the increased slowness of the motion. There is a certain velocity at which these effects mutually neutralise each other, and at this velocity the useful effect is at its maximum.

Suppose the power of the wheel is expended on mov-

ing the millstones without being fed with corn; the velocity of the wheel will then evidently be greater than if the resistance of the grain were opposed to the power. The useful effect will, however, in this case be nothing; the whole power being expended on moving the unloaded machine. Let one pair of stones be now called into action; the velocity will be immediately diminished by the increased resistance, and the useful effect will be estimated by the quantity of flour produced by the single pair of stones in a given time, as one day. Let two pair of stones be now called into action; the resistance being further increased, the velocity will sustain a corresponding diminution. The first pair of stones will produce a less quantity of flour in a day than they did before the second pair were called into action; but this will be more than compensated for by the quantity of flour produced by the second pair, which before were unemployed. The same reason will be applicable if a third pair be called into action, and so on. Now it is evident that the wheel may be required to move so many pairs of stones, that its whole power will be necessary barely to give them motion, none remaining to overcome the additional resistance offered by the corn with which they are fed. This resistance will then stop all motion, and no work will be done or useful effect produced. It is evident that as the machine gradually approaches this limiting state, the useful effect will diminish by degrees before it altogether vanishes; and the point at which it commences so to diminish is that at which the machine has the velocity which produces the greatest useful effect.

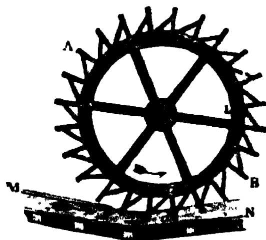
"Experience," says Smeaton, "proves that the velocity of three feet in a second is applicable to the highest overshot wheels as well as to the lowest; and all other parts of the work, being properly adapted thereto, will produce very nearly the greatest effect possible. However, this also is certain from experience, that high wheels may deviate farther from this rule before they will lose their power, by a given aliquot part of the

whole, than low ones can be admitted to do. For a wheel of 24 feet high may move at the rate of 6 feet per second, without losing any considerable part of its power; and, on the other hand, I have seen a wheel of 33 feet high that has moved very steadily and well, with a velocity but little exceeding 2 feet per second."

Undershot Wheel.

(115.) An undershot water wheel is an ordinary wheel turning on an axis, furnished with a number of flat boards placed at equal distances on its rim, and projecting from it in directions diverging from its centre, and having their flat faces at right angles to the plane of the wheel. These boards are called float boards; and such a wheel, of the most common construction, is represented in *fig.* 74. The edge of the wheel, at its lowest

Fig. 74.



point, is immersed in a stream, called a mill-course, and the float boards are intended to receive the impulse of the water as it passes under the wheel. The wheel is thereby caused to revolve in the direction of the stream, with a force depending on the quantity and velocity of the water, and the number, form, and position of the float boards.

The mill-course is usually an artificial canal, carried from the river or other reservoir from which the water is supplied, and conducted, after it has passed the wheel, to some convenient point, where it may be again discharged into the bed of the river. In order that the water

may strike the wheel with the greatest possible force, no more inclination is given to the mill-course A B, *fig.* 75., than is sufficient to give motion to the water in it, until it comes within a short distance of the wheel. There a fall B F is constructed, and the stream having acquired

Fig. 75.



a velocity corresponding to the height of this fall rushes against the float boards, and puts the wheel in motion. The mill-course then has a further fall M V N to carry off the water, which would otherwise impede the advancing float board.

It is found by experience advantageous that the float boards should not precisely converge to the centre of the wheel, but that instead of being perpendicular to the rim of the wheel they should present an acute angle towards the current. By this means force is gained, not merely by the impulse of the water, but in some degree by its weight.

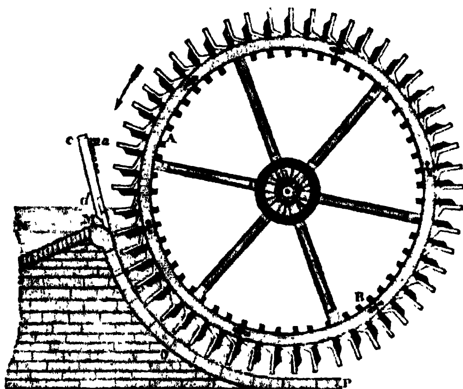
The experiments instituted to determine the best velocity of the wheel, and the best number of float boards, under given circumstances, do not appear to have led to any principles, sufficiently general and certain, to entitle them to notice here.

Breast Wheel.

(116.) A breast wheel partakes of the nature of the overshot and undershot wheels. Like the latter, it is furnished with float boards instead of buckets; but, like the former, it is worked more by the weight of water than by its impulse. The water is delivered at a point M,

fig. 76., nearly on a level with the axis of the wheel, and the mill-course below that point is accommodated to the shape of the wheel, so that the float boards turn nearly

Fig. 76.



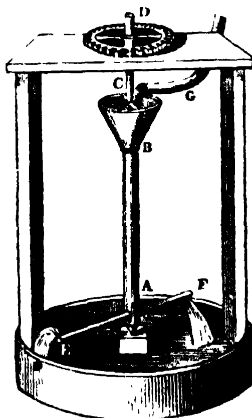
in contact with it. The spaces enclosed by the float boards and the mill-course thus serve the same purpose as buckets in the overshot wheel, and the water enclosed in them turns the wheel by its weight.

Barker's Mill.

(117.) The machine known by this name consists of a hollow upright tube of metal, A B, *fig.* 77., terminating in the upper end B in a funnel, and attached to an upright axis C D, on which a toothed wheel is fixed, from which motion may be communicated to any machinery. The hollow tube B A communicates with a cross tube E F closed at the ends, and the upright tube A is closed at the lower end, and terminates in a point or pivot, which turns freely in a hollow cone adapted to receive it. The whole is enclosed in a frame, and immersed in a reservoir. Let water be supposed to be supplied to the funnel B, from a pipe G, and let the upright and cross tubes be thus filled. The water

standing at the level B, a pressure is excited on every part of the cross tube E F equal to the weight of a column of water whose height is A B. But since this pressure acts equally in every possible direction on the tube E F, it will keep the tube in equilibrium, and no motion will ensue. Let two holes be now pierced in

Fig. 77.



opposite sides of the tube E F, and near the extremities, and let the water be supplied at G as fast as it flows from these holes, so that the level B will be maintained. Those parts of the tube E F, from which the water issues, will thus be relieved from the pressure above mentioned, but the corresponding points on the opposite sides of the tube will still continue to sustain the same pressures. These pressures are, therefore, no longer counterbalanced, since they both tend to make the tube revolve in the same direction. The arms E F will, therefore, immediately commence to revolve, and will turn the upright tube round on the pivot, giving motion at the same time to the toothed wheel above. This motion may be communicated to any kind of machinery.

In some elementary works on hydraulics the operation

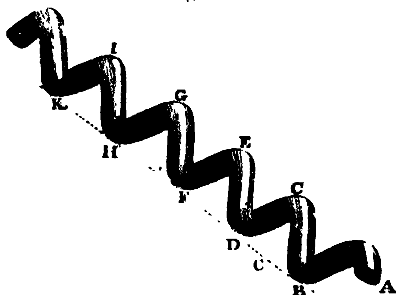
of this machine is explained on totally wrong principles. The motion is said to be produced by the resistance of the air to the issuing water. It would be easy to refute this absurd notion upon theoretical principles; but, perhaps, the argument most intelligible to those who give such an explanation is to bid them try a model of Barker's mill in vacuo. The motion is produced on a principle precisely similar to that which causes a gun to recoil when discharged.

Archimedes' Screw.

(118.) This instrument is said to have been invented by Archimedes when in Egypt, for the purpose of enabling the inhabitants to clear the low grounds from the stagnant water which remained after the periodical overflowings of the Nile. It was also used instead of a pump to clear water from the holds of vessels; and Athenæus states that the memory of Archimedes was venerated by sailors for the benefit thus conferred on them.

The instrument may be presented under different forms, which, however, all agree in principle. Suppose a leaden tube to be bent into a spiral form like a corkscrew, or the worm of a still, as represented in *fig.* 78.

Fig. 78.



Suppose A the extremity to be open and presented upwards, and suppose the screw to be placed in an inclined

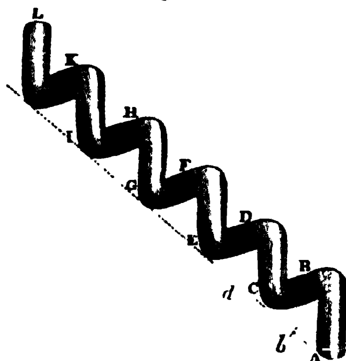
position, as represented in the figure. From its peculiar form and position it is evident that commencing at A, the screw will descend until we arrive at a certain point, B; in proceeding from B to C it will ascend. Thus, B is a point so situate that the parts of the screw on both sides of it are more elevated than it is, and therefore if any body were placed in the tube at B, it could not move in either direction B A or B C, without ascending. Again, the point C is so situate, that the tube on each side of it descends; and as we proceed we find another point, D, which, like B, is so placed that the tube on each side of it ascends, and, therefore, that a body placed at D in the tube could not move in either direction without ascending. In like manner there are a series of points, F, H, &c., continued along the whole length of the spiral, which are circumstanced like B and D; and another series, E, G, &c., which are circumstanced like C.

Let us now suppose a ball, less in size than the bore of the tube, so as to be capable of moving freely in it, to be dropt in at A. As the tube descends from A to B the ball will descend by its weight, as it would down an inclined plane, until it arrive at B. The force which it acquires in its descent will carry it beyond this point, and will cause it to ascend to a small distance towards C; but its weight soon destroys the force which it has retained by its inertia, and after a few oscillations on each side of B, its motion will altogether be destroyed by the friction of the tube, and it will remain at rest at that point.

Now suppose the ball for a moment to be fastened or attached to the tube at B, so as to be incapable of moving in it; and suppose the screw to be turned nearly half round, so that the end A shall be turned downwards, and the point B brought *nearly* to the highest point of the curve A B C. It is evident that the series of points B, D, &c. which were before situate so as to have ascending parts of the tube on each side of them, are now in the very contrary predicament, having inter-

changed situations with the points C, E, &c., as represented in *fig.* 79. The ball, which we supposed attached to the tube, is now hanging as it were on the brow of an acclivity, immediately to the *right* of the highest point at B; for we have supposed the point where the

Fig. 79.



ball was placed to be brought *nearly*, but not exactly, to the highest point. If the ball be now disengaged or detached, it will descend by its gravity from B to C, where it will ultimately rest. The point at which B was placed when the screw was in the position represented in *fig.* 78., is marked *b* in *fig.* 79. In fact, by turning the screw on its axis half round, it must be evident, upon the slightest attention, that no point of it can be really advanced in the direction of its length, and that no other effect can be produced than to cause every point to revolve in a circle round its axis. Thus the point B, *fig.* 78., is transferred from the lowest part of the circle in which it revolves, nearly to the highest, as represented in *fig.* 79.: the ball, therefore, being no longer placed between two ascending parts of the screw, will no longer be prevented from moving in obedience to its gravity; it will have an ascent on one side and a descent on the other, and towards the latter, of course, it must fall. The whole effect, therefore, of the half turn

which we have supposed, is to transfer the ball from the point *b* to the point C, which is, in fact, equivalent to moving it up the inclined plane A G, *fig.* 79., from *b* to C.

Another half turn of the screw will be attended with similar effects. The ball being supposed to be attached to the tube at C, will, when the tube is restored to the position represented in *fig.* 78., cause the ball to stand on the brow of an acclivity descending from C to D. If the ball, therefore, be again disengaged, it will fall to D, where it will again rest. By this means the ball is therefore carried up the inclined plane from *c* to D, as in *fig.* 78., or, what is the same, from C to *d*, in *fig.* 79.

It is clear that, by continuing this reasoning, we could show, that, under the circumstances supposed, the ball would be gradually transferred from the lowest point of the inclined plane to the highest as far as the screw extends.

We have supposed the ball to remain attached to the screw at B until a half turn of the screw is nearly completed, and not until then to be detached. But suppose that the ball is detached when a very small part of a turn has been made: the point B will thus be brought into a situation a little above that at which it has an ascending branch of the screw on each side of it; it will then have a descending part on that side from which it was moved; if detached it will consequently descend in that direction, and will cease to move when it arrives in that part of the screw where it will have an ascending branch at each side of it. Now suppose the ball not to be attached to the tube, but merely to lie in it, the motion which we have here supposed to be effected at intervals, and to be interrupted by the ball being occasionally attached to the tube so as to prevent it moving, will, in fact, take place continuously, and the ball will be carried up the inclined plane, not by distinct efforts separated by intervals, but by one uninterrupted and continuous motion.

All that has been said of a ball in the tube would be

equally true, if a drop or any quantity of a liquid were contained in the tube instead of the ball. Therefore, if the extremity of the screw were immersed in a well or reservoir of water, so that the water would by its weight or pressure be continually forced into the extremity of the tube, it would, by turning the tube, be gradually carried along the spiral to any height to which it may extend.

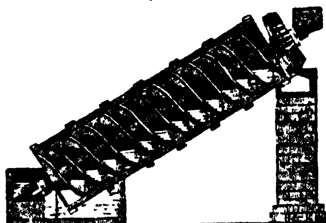
From the explanation given above it is clear, that it is essential to the performance of this machine that the elevation of the spiral above the horizontal position should not exceed a certain limit. In fact, in each spire of the tube a certain point must be found, on either side of which the tube ascends. Now it is apparent that the tube may be so elevated in its position, that the part of the tube which proceeds towards the lower extremity of the screw will descend in every part of the tube: this will be quite evident if the screw be supposed first to be placed in a perfectly upright position. Under such circumstances it is obvious, that if the ball were placed any where in the tube it would fall down to the lowest point: a slight inclination from the vertical position will not prevent this from happening; but if the screw receive such an inclination, that in each spire a point will be found so placed that the part proceeding towards the lower extremity shall ascend, then the ball placed at such a point will remain at rest; and, if the screw be turned, will ascend, as already explained.

In practice, the spiral channel through which the water is carried is not in the form of a tube. A section of the instrument, as used in practice, is represented in *fig.* 80.

The screw possesses an advantage over common pumps in being capable of raising water which is not pure, being mixed with gravel, weeds, or sand. The screw may be kept in a state of revolution by any of the usual moving powers. Dr. Brewster mentions that an excellent engine of this description was erected, in 1816, at Hurlet alum works, upon the water of Levern near Paisley. This engine was moved by a water wheel,

which communicated by a long shaft with the screw; a bevelled wheel was constructed on the screw, which worked in another bevelled wheel on the extremity of the shaft; another bevelled wheel on the axle of the

Fig. 80.



water-wheel, worked in a corresponding wheel on the other extremity of the shaft. The screw was thus kept in constant revolution by the fall of water which supplied the reservoir, from whence the same water was to be raised by the screw itself.

The Sluice Governor.

(119.) In explaining the operation of water wheels, it was shown that there was a certain velocity at which the useful effect resulting from them is a maximum. Any deviation from this rate of motion, whether by increase or decrease, must be attended by a corresponding loss of power: but, since the water in the mill course must, from obvious natural causes, be subject to considerable fluctuations in its quantity and force, the velocity which it would communicate to the wheel would undergo proportionate variations. It is, therefore, necessary to provide some means of controlling the quantity of water and measuring out the power, so as to maintain a steady velocity in the wheel.

Independently of the fluctuating energy of the power, changes of velocity are liable to be produced by occasional changes in the amount of the load or resistance. Thus, in a corn mill, if a greater or less number of

pairs of stones are in action at one time than at another, a proportionately increased or diminished supply of the moving power will be necessary to give the wheel the same velocity.

The necessity of regulating the motion of the wheel does not, however, alone arise from the advantage of causing the moving power to produce the greatest possible effect. The nature of the work to be performed is almost in every case such as requires the machinery to be moved with a certain velocity. Thus, in a corn mill, if the speed surpass a certain limit, the flour becomes heated and injured. Spinning and weaving machinery, in like manner, requires to be conducted at a certain rate, any irregularity in which must injure or destroy the fabric of the manufacture.

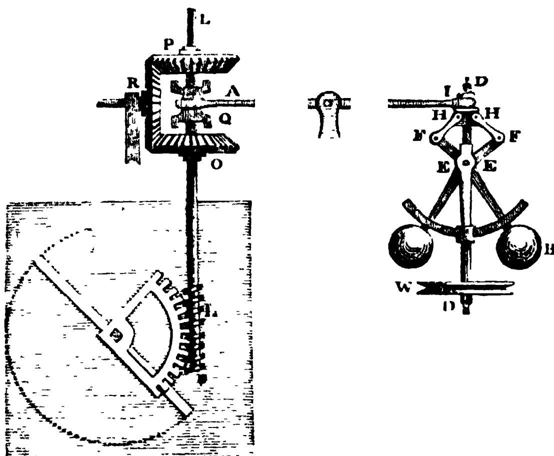
For all these reasons the power, whatever it be, which gives motion to machines or factories, must be so regulated, as under every change of circumstances to produce a uniform motion; and the same contrivance, usually called a *governor*, has been found to be applicable to moving powers, differing very much in their nature, such as water, steam, &c. This instrument has already been described in the treatise on Mechanics in this Cyclopædia *, in its application to the steam-engine. It may not be uninteresting here, however, to explain its application in regulating the motion of a water wheel.

D D, *fig.* 81., is a shaft to which a grooved wheel W is attached; round this wheel a rope is carried, which is moved by a corresponding wheel placed on some shaft in the machinery moved by the water wheel. B B are two heavy balls attached to rods B E F, which play upon a joint at E. These are connected by joints at F, with other rods F H, which are jointed upon a ring at H, which slides up and down the shaft D D. This ring is connected with the end, I, of a lever, whose fulcrum is at G, and which has at the other extremity a ring or fork, A, which embraces the axis of a double clutch, Q, in such a manner as to allow this axis to turn freely

* Cab. Cyc Mechanics, chap. xvi.

within it. This clutch Q is itself placed upon a shaft or axis, on which it is capable of sliding freely up or down, but on which it cannot turn without causing the shaft to revolve with it. The effect of the arrangement here described is evident.

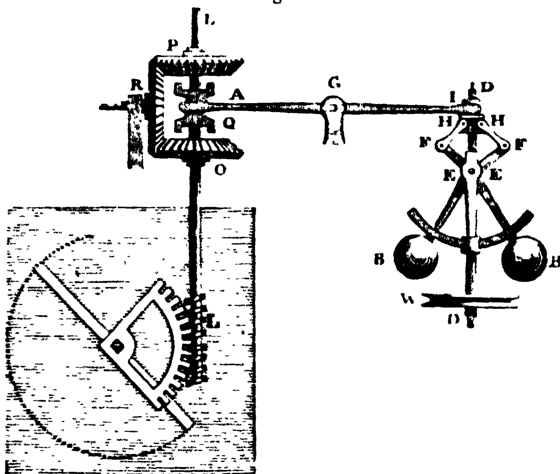
Fig. 81.



If the balls B B be raised from the axis and drawn, as it were, asunder, the rods turning on the pivot E will cause the extremities F also to separate, and increase their distance from the axis. This will draw the rods F H in the same direction, and cause the ring H to descend, drawing the extremity I of the lever with it. The other extremity A will thus be raised. If, on the other hand, the balls B B be brought nearer the axis, the contrary effects will be produced, the extremity I being raised, and the extremity A lowered. In the one case the fork A will raise the clutch, and in the other will lower it, causing it to slide along the shaft L M. On this shaft are placed two bevelled wheels O P which move loosely upon it, turning independent of the shaft.

A third bevelled wheel R works in both of these, turning them in opposite directions. This wheel receives its motion from the shaft D D, with which it is connected by other wheels not represented in the figure.

Fig. 81.



Under the circumstances here explained the shaft L M is at rest, having the bevelled wheels O P turning freely on it in opposite directions, and the machinery is supposed to be moving with the proper velocity.

Now suppose this velocity from any cause to undergo a sudden increase. By reason of the increased centrifugal force arising from the whirling motion, the balls B B will recede from the shaft D D, and, as already explained, will cause the clutch Q to rise towards the bevelled wheel P. This clutch bears four projecting pieces on the face presented towards the bevelled wheel, which are pressed by the end A of the lever into corresponding cavities in that wheel. When this takes place, the clutch is compelled to revolve with the wheel, and the axis revolves with the clutch.

Again, let it be supposed that the velocity of the machinery becomes diminished, from any cause. The centrifugal force produced by the whirling motion of the balls B B being thus diminished, the balls will have a less tendency to recede from the axis D D, and will therefore fall towards it: this, as already explained, will cause the extremity of the lever A to move downwards on the shaft L M, and projecting pieces on the opposite face of the clutch Q will fall into cavities on the bevelled wheel O, in the same manner as already described with respect to the bevelled wheel P. The clutch Q, and the shaft L M, will now be compelled to revolve with the wheel O, in a direction opposite to that in which it revolved in the former case. It will therefore be perceived that any deviation in the velocity of the machinery from that velocity which, from its nature, it ought to have, will cause the shaft L M to turn in the one direction or in the other, according as the motion is increased or slackened. This shaft communicates by means of an endless screw, with a rack or toothed arch, which works a sluice gate, as represented in the figure; and when the shaft is turned in one direction, it closes the gate so as to diminish the supply of water, and when it is turned in the opposite direction, it opens the gate so as to increase its supply. Thus, when the machinery receives an undue increase of speed, the sluice-gate is closed, and the supply of power diminished, and the velocity checked: when the motion is reduced to its proper rate, the balls B B fall to their proper distance from the axis, and disengage the clutch from the bevelled wheels, and all further action upon the sluice-gate is stopped. When the machinery receives an undue diminution in its rate of motion, the same effect is produced by the other bevelled wheel opening the flood-gate. When the proper rate of motion is restored, the balls B B rise to their first position and disengage the clutch.

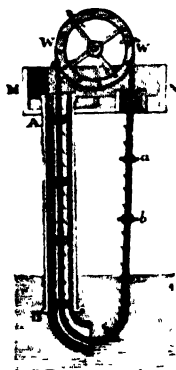
Thus the machinery is constantly caused to move at a uniform rate, and the governor is adjusted in the first instance, so that the clutch shall be disengaged from both

bevelled wheels when the machinery is moving at the proper rate.

The Chain Pump.

(120.) The chain pump is a contrivance for lifting water in a cylinder by having a movable bottom fitting water-tight in it, which can be moved to the top, driving all the contents of the cylinder before it. In *fig.* 82.

Fig. 82.



A B is a cylinder, the lower part of which is immersed in a well or reservoir, and the upper part enters the bottom of a cistern into which the water is to be raised. An endless chain is carried round the wheel at the top, and is furnished at equal distances with pistons or movable bottoms which fit water-tight in the cylinder. As these successively enter the cylinder, they carry the water up before them, which is discharged into the cistern at the mouth of the cylinder above. The moving power is usually applied by a winch or otherwise to the wheel. The cylinder may be placed in an inclined position, in which it works to more advantage than when vertical. The effect is greatest when the distance between the pistons is equal to their diameters.

A

TREATISE

ON

PNEUMATICS.

A

TREATISE

ON

PNEUMATICS.

CHAP. I.

INTRODUCTION.

FORM OF BODIES.—HOW AFFECTED BY HEAT.—AERIFORM STATE. —ELASTICITY.—DIVISION OF MECHANICAL SCIENCE.—COMPRESSIBILITY AND INCOMPRESSIBILITY.—PERMANENTLY ELASTIC FLUIDS.—VAPOUR.—STEAM.—ATMOSPHERIC AIR.

(121.) The effects which the presence of heat produces on the physical state of a body have been noticed in the first chapter of our treatise on Hydrostatics. The opposite principles of cohesion and repulsion are made to change their relation by the variation which the latter undergoes on the increase or diminution of the heat contained in the body. The liquid state in which bodies are contemplated in hydrostatics is one in which these antagonist principles are maintained in equilibrium, or nearly so. In the department of physics, which we are now about to investigate and explain, bodies are contemplated in that state which results from the predominant influence of the repulsive principle. The constituent particles of the body under consideration repel each other so actively, that they fly asunder and separate, so that the whole mass will dilate itself to any extent,

unless its expansion be limited by the operation of adequate forces, confining it within certain dimensions.

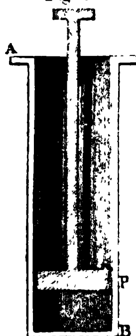


Fig. 1.

The most obvious and familiar example of the physical state here referred to is that of atmospheric air. Let A B, *fig.* 1., be a cylinder in which a piston P moves air-tight, and let us suppose that a small portion, as a cubic inch of atmospheric air in its common state, be contained between the piston and the bottom of the cylinder: suppose the piston now drawn upwards, as in *fig.* 2., so as to increase the space below it to two cubic inches. The air will not continue to fill one cubic inch, leaving the other cubic inch unoccupied, as would be the case if a solid or liquid had been beneath the piston in the first instance; but it will expand or dilate until it spread itself through every part of the two cubic inches, so that every part, however small, of this space, will be found occupied by air. Again, suppose the piston further elevated, so that the space below it shall amount to three cubic inches; the air will still further expand, and will spread itself through every part of the increased space; and the same effect would continue to be produced, to whatever extent the space might be increased through which the air is at liberty to circulate.

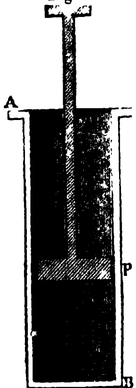


Fig. 2.

This quality of expanding, as the surrounding limits are enlarged, has caused air and every body existing in that state which gives it the like property to be called an *elastic fluid;* and, in contradistinction to this, liquids whose particles do not repel each other, so as to produce the same effect, are

called *inelastic fluids*. Thus the mechanical theory of inelastic fluids forms the subject of HYDROSTATICS, and that of elastic fluids the subject of PNEUMATICS. As water, the most common of liquids, is taken as the type or example of all others, the name Hydrostatics is taken from two Greek words, signifying water and equilibrium. In like manner, air being selected as the most familiar example of all elastic fluids, the name *Pneumatics* is borrowed from a Greek word signifying *air* or *breath*.

(122.) The qualities depending on the aeriform state cannot properly be taken as the basis of the classification of the species of bodies, because, by the agency of heat, all bodies may be reduced to this state ; and although in every instance the question has not been brought to the actual test of experiment, yet there are the strongest analogies in support of the conclusion, that all aeriform bodies, including the atmosphere itself, are capable of being reduced to the liquid, and even to the solid form. We are, therefore, to regard the properties investigated in the three branches of physical science respecting solids, liquids, and gases, not as peculiar properties of distinct species of bodies, but as qualities which will appertain to all bodies whatsoever, according as they are affected by certain external agencies.

Water affords a convenient example of the truth of these observations. In the state of ice, its properties come under the dominion of mechanics *, commonly so called. When exposed to temperatures which no longer permit its existence in the solid state, it loses some of those properties and acquires others, which hand it over to the sway of Hydrostatics. A further increase of temperature will cause it to pass into the state of vapour or steam, and impart to it those qualities which appropriate its investigation to Pneumatics.

* In the correct application of the term MECHANICS includes the doctrines of equilibrium and motion of bodies in all the three states of solid, liquid, and gas, but its more popular and vulgar application is confined to the equilibrium and motion of solids. A distinct appellation is wanted for the latter branch of the science The title STEREOSTATICS has been suggested.

Since, by imparting heat continually to a body, it is made to pass successively from the solid to the liquid, and from the liquid to the gaseous state, and by continually abstracting heat it may be transferred in the contrary direction from the gaseous to the liquid, and from the liquid to the solid state, it might, perhaps, be inferred that all bodies in the solid state must be colder than those in the liquid, and all liquids colder than bodies in the gaseous state. Such an inference, however, may be proved to be unfounded in two ways.

1. Bodies of different kinds pass from the one to the other of these states at different temperatures; thus, to cause water to pass from the liquid to the solid state, it is necessary to reduce its temperature to 32° of the common thermometer; but if we would reduce quicksilver from the liquid to the solid state, a much more diminished temperature must be produced. Thus it may be perceived that water in the solid state may be at a much higher temperature than mercury in the liquid state. Again, to cause water to pass from the liquid to the gaseous state, it is necessary, under ordinary circumstances, to raise its temperature to 212° of the common thermometer. Now to cause mercury to pass from the liquid to the gaseous state would require its temperature to be raised to above 650°. Hence it appears that water in the aeriform state may have a much lower degree of heat than mercury in the liquid state; but

2. The error that we have just noticed arises partly from the supposition that all the heat which a body contains is in a state to affect the senses or the thermometer. In other words, it is supposed that so long as a body continues to receive heat from fire applied to it, or from any other source, so long its temperature will increase, and the body will become hotter. That this supposition is erroneous is easily proved. Let a quantity of ice at the temperature of 32° be placed in a vessel containing six times its quantity of water at the boiling heat. The water will immediately begin to lose its heat by imparting it to the ice; but, meanwhile, the temperature of the ice will not

be increased. After the lapse of a sufficient time, the whole of the ice will be liquefied and intermixed with the water; and it will be found that the entire contents of the vessel in the liquid state have the temperature of only 32°. Now here it is obvious that the water originally contained in the vessel has lost so much of its heat as to be reduced to the temperature of the ice. But, on the other hand, the ice has not shown an increased effect on the thermometer or on the senses, notwithstanding the large quantity of heat which it has most certainly imbibed. The development of the theory, founded upon this remarkable fact, does not belong to the department of physics with which we are at present engaged; but the mere statement of the fact is sufficient to prove that we are not to infer, that because steam, and the water from which it has been raised, produces the same effect on the thermometer or the senses, they therefore contain the same quantity of heat, and that the fact of one body being hotter or colder than another does not justify the inference that the one *contains* more or less heat than the other.

(123.) As an elastic fluid has the property of dilating itself when the limits of the space within which it is confined are enlarged, it is also characterised and distinguished from solids and liquids by its power of yielding to any force exceeding the energy with which its particles repel each other, and tending to contract the limits of the space within which it is enclosed. This quality is called *compressibility;* and although under extreme circumstances it is proved by experiment to exist in a slight degree in liquids, and, probably, is a quality in which all bodies in some degree participate; yet it belongs so conspicuously to bodies in the gaseous form, that they are frequently denominated *compressible fluids*, in contradistinction to liquids, which are often called *incompressible fluids*. Upon the application of great force liquids are found to yield in a very small degree in their dimensions; this effect, however, is so slight, and produced under such extreme circumstances, that it is found that

a mechanical theory of liquids, proceeding upon their assumed incompressibility, gives results which have no variation from the actual phenomena of any practical importance. Such, however, is not the case with elastic fluids; they yield upon the application of inconsiderable pressure; and they allow their dimensions to be contracted in all cases to a very great extent, and in many without any practical limit. The consequences and laws of compressibility and expansibility, as they are found to exist in elastic fluids, will be more fully noticed hereafter.

(124.) Of the various elastic fluids which are observed in nature, some have never been found in the liquid form; and many of these have never been by any process of art reduced to that form; such, for example, is atmospheric air: bodies of this kind are called *permanently elastic fluids.* By these words, however, the impossibility of their reduction to the liquid state is not intended to be assumed; it is only intended to express the fact, that such reduction has not been made. The name "gases" is also commonly applied to bodies of this class. When bodies more commonly exist in the liquid state, but by natural heat and other causes sometimes receive the elastic form, the elastic fluid is called *vapour:* thus, for example, when heat is applied to quicksilver, the elastic fluid which is produced is called the *vapour* of quicksilver, and the process is called *vaporisation.* The lighter liquids, such as æther, are converted into vapour by the common temperature of the atmosphere; the vapour of water is called *steam.* This term *steam,* however, is sometimes, though not with such strict propriety, used synonymously with the word *vapour.*

(125.) Those mechanical properties of elastic fluids which have generally been assigned to PNEUMATICS are the qualities which are found in atmospheric air; many of these qualities extend without modification to all elastic fluids whatsoever; but there are some of them which, especially when applied to vapour, require to be restricted and modified by various circumstances which

belong rather to the theory of heat than to the subject of the present treatise. There are also many circumstances to be attended to in explaining the properties of various gases, which belong to those departments of physics in which the production and constitution of these gases are explained. The province of PNEUMATICS may, therefore, be considered as chiefly and immediately confined to the investigation of the mechanical properties of the atmosphere; it being at the same time understood that the various theorems which shall be established are to be carried into other departments of physics, there to undergo such restrictions and modifications as will render them applicable to vapours and the various species of gases.

CHAP. II.

PROPERTIES OF ATMOSPHERIC AIR.

ATMOSPHERIC AIR IS MATERIAL. — ITS COLOUR. — CAUSE OF THE BLUE SKY. — CAUSE OF THE GREEN SEA. — AIR HAS WEIGHT. — EXPERIMENTAL PROOFS. — AIR HAS INERTIA. — EXAMPLES OF ITS RESISTANCE. — IT ACQUIRES MOVING FORCE. — EXAMPLES OF ITS IMPACT. — AIR IS IMPENETRABLE. — EXPERIMENTAL PROOFS.

(126.) THE atmosphere is the thin transparent fluid which surrounds the earth to a considerable height above its surface, and which, in virtue of one of its constituent elements, supports animal life by respiration, and is necessary also to the due exercise of the vegetable functions. This substance is generally, but erroneously, regarded as invisible. That it is not invisible may be proved by turning our view to the firmament: that, in the presence of light, appears a vault of an azure or blue colour. This colour belongs not to any thing which occupies the space in which the stars and other celestial objects are placed, but to the mass of air through which these bodies are seen. It may probably be asked, if the air be an azure-coloured body, why is not that which immediately surrounds us perceived to have this azure colour, in the same manner as a blue liquid contained in a bottle exhibits its proper hue? The question is easily answered.

There are certain bodies which reflect colour so faintly, that, when they exist in limited quantities, the portion of coloured light which they transmit to the eye is insufficient to produce sensation, that is, to excite in the mind a perception of the colour. Almost all semi-transparent bodies are examples of this. Let a champagne glass be filled with sherry, or other wine of that colour; at the thickest part, near the top of the glass, the wine

will strongly exhibit its peculiar colour, but as the glass tapers, and its thickness is diminished, this colour will become more faint; and, at the lowest point, it will almost disappear, the liquid seeming nearly as transparent as water.

Now let a glass tube, of very small bore, be dipped in the same wine, and the finger being applied to the upper end, let it be raised from the liquid; the wine will remain suspended in the tube; and if it be looked at through the tube it will be found to have all the appearance of water, and to be colourless. In this case there can be no doubt that the wine in the tube has actually the same colour as the liquid of which it originally formed a part; but existing only in a small quantity, that colour is transmitted to the eye so faintly as to be inefficient in producing perception.

The water of the sea exhibits another remarkable example of this effect. If we look into the sea where the water has considerable depth, we find that its colour is a peculiar shade of green; but if we take up a glass of the water which thus appears green, we shall find it perfectly limpid and colourless. The reason is, that the quantity contained in the glass reflects to the eye too small a quantity of the colour to be perceivable; while the great mass of water, viewed when we look into the deep sea, throws up the colour in such abundance as to produce a strong and decided perception of it.

The atmosphere is in the same circumstances: the colour, from even a considerable portion of it, is too faint to be perceptible. Hence the air which fills an apartment, or which immediately surrounds us when abroad, appears colourless and perfectly transparent. But when we behold the immense mass of atmosphere through which we view the firmament, the colour is reflected with sufficient force to produce distinct perception. But it is not necessary for this that so great an extent of air should be exhibited to us as that which forms the whole depth or thickness of the atmosphere. Distant mountains appear blue, not because that is their colour, but

because it is the colour of the medium through which they are seen.

Although the preceding observations belong more properly to optics than to our present subject; yet still, since the exhibition of colour is one of the manifestations of the presence of body, they may not be considered as foreign to an investigation of the mechanical properties of atmospheric air. The mind unaccustomed to physical enquiries finds it difficult to admit that a thing so light, attenuated, impalpable, and apparently spiritual, should be composed of parts whose leading properties are identical with those of the most solid and adamantine masses. The knowledge that we see the air must at least prepare the mind for the admission of the truth of the proposition that air is a body.

•(127.) Among the properties which are observed to appertain to matter, and which, as far as we know, are inseparable from it, in whatever form, and under whatever circumstances it exists, weight and inertia hold a conspicuous place. To be convinced, therefore, that air is material we ought to ascertain whether it possesses these properties. In the subsequent parts of the present treatise, we shall have numerous proofs of this; but it will at present be convenient to demonstrate it in such a manner that we shall be warranted in assuming it, in some of the explanations which we shall have to offer.

(128.) The most direct proof that air has weight is the fact, that if a quantity of it be suspended from one arm of a balance, it will require an absolute weight to counterpoise it in the opposite scale. By the aid of certain pneumatical engines, the nature of which will be explained hereafter, but the operation and effects of which will for the present be assumed, this may be experimentally established.

Let a vessel, containing about two quarts, be formed of thin copper, with a narrow neck, in which is placed a stopcock, by turning which the vessel may be opened or closed at pleasure. Let two instruments be provided called syringes, one the exhausting syringe, and the other

the condensing syringe. The nature of these instruments will be hereafter explained. Let the exhausting syringe be screwed upon the neck of the vessel, and let the stopcock be opened, so that the interior of the vessel shall have free communication with the bottom of the syringe; if the syringe be now worked, a large portion of the air contained in the vessel may be withdrawn from it. When this has been done, let the stopcock be closed to prevent the admission of air, and let the vessel be detached from the syringe. Let it then be placed in the dish of a well constructed balance, and accurately counterpoised by weights in the opposite scale. The weight which is thus counterpoised is that of the vessel, and the small portion of air which remains in it, if the latter have any weight. Let the stopcock be now opened, and the external air will be immediately heard rushing into the vessel. When a small quantity has been thus admitted, let the stopcock be again closed. It will be found that the copper vessel is now heavier, in a small degree, than it was before the air was admitted, for the arm of the balance from which it is suspended will be observed to preponderate. Let such additional weights be placed in the opposite scale as will restore equilibrium. The stopcock being now once more opened, the air will be observed to rush in as before, and will continue to do so until as much has passed into the vessel as it contained before the exhausting syringe was applied. The weight of the vessel will now be observed to be further increased, the end of the beam from which it is suspended preponderating,

These facts are perhaps sufficient proofs that air has weight: but the experiment may be carried further. Let the condensing syringe be now attached to the neck of the vessel, and let the stopcock in the neck be opened so as to leave a free communication between the vessel and the bottom of the syringe. The construction of this intrument, which will be explained hereafter, is such, that by working it an increased quantity of air may be forced into the vessel to any extent which the strength

of the vessel is capable of bearing. A considerably increased quantity of air being thus deposited in the vessel, let the stopcock be closed so as to prevent its escape. The vessel being detached from the syringe, is restored to the dish of the balance; the weights which counterpoised it before the increased quantity of air was forced in still remaining unchanged in the opposite scale. The vessel will now no longer remain counterpoised, but will preponderate, and will require an increased weight in the opposite scale to restore it to equilibrium.

In this experiment we see that every increase which is given to the quantity of air contained in a vessel produces a corresponding increase in its weight, and that every diminution of the quantity of air it contains produces a corresponding diminution in its weight. Hence we infer, that the air which is introduced into or withdrawn from the vessel has weight, and that it is by the amount of its weight that the weight of the vessel is increased or diminished.

We shall hereafter have many other instances of the gravitation of atmospheric air; but we shall, for the present, assume the principle that air has weight, founded on the experimental proof just given.

(129.) That air in common with all other bodies possesses the quality of inertia, numerous familiar effects make manifest. Among the effects which betray this quality in solid bodies, is the fact that, when one solid body puts another in motion, the former loses as much force as the latter receives. This loss of force is called resistance, and is attributed to the quality of inertia, or inability in either the striking or struck body to call into existence more force in a given direction than previously existed. When the atmosphere is calm and free from wind, the particles of air maintain their position, and are in a state of rest. If a solid body, presenting a broad surface, be moved through the air in this state, it must, as it moves, drive before it and put in motion those parts of the air which lie in the space through which it passes. Now, if the air had no inertia, it would require

no force to impart this motion to them, and to drive them before the moving solid; and as no force would in that case be imparted to the air, so no force would be lost by the solid: in other words, the solid would suffer no resistance to its motion.

But every one's experience proves this not to be the case. Open an umbrella, and attempt to carry it along swiftly with its concave side presented forwards; it will immediately be felt to be opposed by a very considerable resistance, and to require a great force to draw it along. Yet this force is nothing more than what is necessary to push the air before the umbrella.

On the deck of a steam boat, propelled with any considerable speed, we feel on the calmest day a breeze directed from the stem to the stern. This arises from the sensation produced by our body displacing the air as we are carried through it.

It is the inertia of the atmosphere which gives effect to the wings of birds. Were it possible for a bird to live without respiration, and in a space void of air, it would no longer have the power of flight. The plumage of the wings being spread, and acting with a broad surface on the atmosphere beneath them, is resisted by the inertia of the atmosphere, so that the air forms a fulcrum, as it were, on which the bird rises by the leverage of its wings.

As a body at rest manifests its inertia by the resistance which it offers when put in motion, so a body in motion exhibits the same quality by the force with which it strikes a body at rest. We have seen examples of the resistance which the atmosphere at rest offers to a body in motion; but the force with which the atmosphere in motion acts upon a body at rest is exhibited by examples far more numerous and striking. Wind is nothing more than moving air, and its force, like that of every other body, depends on the quantity moved and the speed of the motion. Every example, therefore, of the effects of the power of wind is an example of the inertia of at-

mospheric air. In a windmill, the moving force of all the heavy parts of the machinery is derived from the moving force of the wind acting upon the sails, and the resistance of the work to which the mill is applied is overcome by the same power. A ship is propelled through the deep, and the deep itself is agitated and raised in waves by the inertia of the atmosphere in motion. As the velocity increases, the force becomes more irresistible; and we find buildings totter, trees torn from the roots, and even the solid earth itself yield before the force of the hurricane.

(130.) Since air may be seen and felt, since it has colour and weight, and since it opposes resistance when acted upon, and strikes with a force proportionate to the speed of its motion, we can scarcely hesitate to admit that it has qualities which entitle it to be classed among material substances: but one other quality still remains to be noticed, which, perhaps, decides its title to materiality more unanswerably than any of the others. Air is impenetrable; it enjoys that peculiar property of matter by which it refuses admission to any other body to the space it occupies, until it quit that space. This property air possesses as positively as adamant. The difficulty which is commonly felt in conceiving the impenetrability of substances of this nature, arises partly from confounding the quality of impenetrability with that of hardness, and partly from not attending to the fact that, when a body moves through the air, it drives the air before it in the same manner as a vessel moving through the water propels that fluid.

Let a bladder be filled with air, and tied at the mouth; we shall then be able to feel the air it contains as distinctly as if the bladder were filled with a solid body. We shall find it impossible so long as the air is prevented from escaping to press the sides of the bladder together; and if the bladder be submitted to such severe pressure as may be produced by mechanical means, it will burst before the air will allow it to collapse.

That air will not allow the entrance of another body

into the space where it is present, may also be proved by the following experiment.

Let A B, *fig.* 3., be a glass vessel open at the end A, and having a short tube from the bottom, furnished with a stopcock C. Let D E, *fig.* 4, be another glass vessel

Fig. 3.

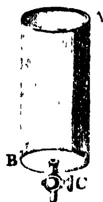


Fig. 4.

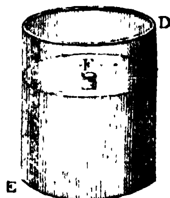


Fig. 5.



containing water. On the surface of this water let a small piece of cork F float. Let the vessel A B, having the stopcock C closed, be now inverted; let its mouth A be placed over the cork F, and let it thus be pressed to any depth in the reservoir D E. If the air in A B were capable of permitting the entrance of another body into the space in which it is present, the water in the reservoir D E would now enter at the mouth of the vessel A, and rising in it would stand at the same level within the vessel A B as that which it has without it. But this is not found to be the case. When the vessel A B is pressed into the reservoir, the surface of the water within A B will be observed still near the mouth A as will be indicated by the position of the cork which floats upon it, and as is represented in *fig.* 5. It appears, therefore, manifestly, that, whatever be the cause, the water is excluded from the vessel A B. That this cause is the presence of the air included in the vessel is proved by opening the stopcock C, and allowing the air to escape. By the established principles of hydrostatics, the surface of the water within the vessel A B exerts an upward pressure proportionate to the depth of that sur-

face below the surface of the water exterior to the vessel A B. This pressure, acting upon the air inclosed in the vessel A B, forces it out the moment the stopcock C is opened, and immediately the surface of the water within A B rises to the level of the surface without it.

We have stated that the surface of the water within A B remains *nearly* at the mouth of that vessel when it is plunged in the reservoir. It would remain *exactly* at the mouth, if air were incompressible; but, on the contrary, this fluid is highly compressible, allowing itself to be forced into reduced dimensions by the application of adequate mechanical force. It is necessary, however, not to confound compressibility with penetrability. So far from these qualities being identical, the one implies the absence of the other. A body is compressible when the forcible intrusion of another body into the space within which it is confined causes its particles to retreat, and to accommodate their arrangement to the more limited space within which they are compelled to exist. The very fact of their thus retreating before the intruding body is a distinct manifestation of their impenetrability. If they were penetrable, the body would enter the space in which they were confined, without driving them before it, or otherwise disturbing their arrangement.

CHAP. III.

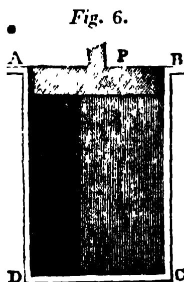
ELASTICITY OF AIR.

ELASTIC AND COMPRESSING FORCES EQUAL. — LIMITED HEIGHT OF THE ATMOSPHERE. — ELASTICITY PROPORTIONAL TO THE DENSITY. — EXPERIMENTAL PROOFS. — INTERNAL AND EXTERNAL PRESSURE ON CLOSE VESSELS CONTAINING AIR.

(131.) THE elasticity and compressibility of air have been already noticed. In the present chapter we propose to examine and explain these qualities in more detail.

It will be evident, upon the slightest reflection, that the elasticity of air must be equal to the force which is necessary to confine it within the space it occupies. Let us suppose that A B, *fig.* 6., is a cylinder, having a pis-

Fig. 6.



ton P fitting air-tight at the top; and let us imagine that this piston P is not acted upon by any external force, having a tendency to keep it in its place. If the cylinder below the piston be filled with air, this air will have a tendency, by virtue of its elasticity, to expand into a wider space; and this tendency will be manifested by a pressure exerted by the air on all parts of the surfaces which confine it. The piston P will,

therefore, be subject to a force tending to displace it and drive it from the cylinder, the amount of which will be the measure of the elasticity of the air beneath it. Now, if this piston be not subject to the action of a force directed inwards, exactly equal in amount to the pressure thus excited by the elastic force of the air, it cannot maintain its position. If it be subject to an inward force of less amount than the elastic pressure, then the latter will prevail, and the piston be forced *out*. If it be subject to an inward force greater in amount than the elastic pressure, then the former will prevail, and the piston will be forced *in*, the air being compelled to retreat within a more confined space. In no case, therefore, can the piston maintain its position, except when it is subject to an inward pressure exactly equal to the elastic force of the air inclosed in the cylinder.

The property of elasticity renders it necessary that, in whatever state air exist, it shall be restrained by adequate forces of some definite amount, and which serve as antagonist principles to the unlimited power of dilatation which the elastic property implies. " In all cases which fall under common observation, air is either restrained by the resistance of solid surfaces, or it is pressed by the incumbent weight of the mass of atmosphere placed above it. It may be asked, however, whether it will not follow from this, that the extent of our atmosphere is infinite? for that, as we ascend in it, the weight of the superior mass of air must be gradually and unceasingly lessened; and, therefore, the force which resists the expansive principle being removed by degrees, the fluid will spread through dimensions which are subject to no limitation. Although it is undoubtedly true that these considerations lead us justly to conclude that our atmosphere extends to a very great distance from the surface, and that the higher strata of it are attenuated to a degree which not only exceeds the powers of art to imitate, but even outstrips the powers of imagination to conceive; yet still the understanding can suggest a definite limit to this expansion. Numerous physical ana-

logies * favour the conclusion, that the divisibility of matter has a limit, or that all material substances consist of ultimate constituent particles or atoms, which admit of no further subdivision, and on the mutual relations of which the form and properties of the various species of bodies depend.

Now, those ultimate particles of the air are endued with a certain definite weight, because it is the aggregate of their weights which forms the weight of any mass of air. It is a fact established by experiment, that in proportion as air expands, its elastic force is diminished; and, therefore, if it continue to expand, it will at length attain a state of attenuation in which the disposition of its constituent particles to separate by their elasticity is so far diminished, as not to exceed the gravity of those constituent particles themselves. In this state the two forces will be in equilibrium, and the elastic force being neutralised, the particles will no longer be dilated.

(132.) In these observations we have assumed a principle which is of the last importance in pneumatics, and which, indeed, may be regarded as forming the basis of this part of physical science, in the same manner as the power of transmitting pressure is the fundamental principle of hydrostatics. This latter principle, indeed, also extends to elastic fluids; and all the consequences of the free transmission of pressure, which do not also involve the supposition of incompressibility, are applicable to elastic fluids with as much truth as to liquids. But the principle to which we now more especially refer, and which may be looked upon as the chief characteristic of this form of body, and necessary to render definite the notion of their elasticity, may be announced as follows: —

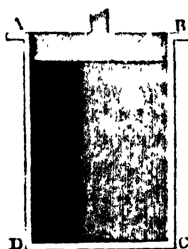
"The elastic force of any given portion of air is augmented in exactly the same proportion as the space within which it is enclosed is diminished; and its elastic force is diminished in exactly the same proportion as

* Cab. Cyc. Mechanics, chap ii.

the space through which it is allowed to expand is augmented."

To explain this, let A B C D, *fig.* 7., be conceived to be a cylinder, in which a piston A B moves air-tight and

Fig. 7.

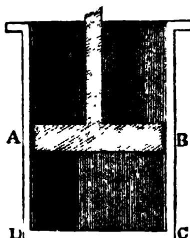


without friction; and let us suppose the distance of the lower surface A B of the piston from the bottom D C of the cylinder to be 12 inches. Let air be imagined to be inclosed below the piston, and let us suppose that the elastic force of this air is such as to press the piston with a force of 16 ounces. From what has been already stated (131.), it is clear that to maintain the piston in its place, it is necessary that it should be pressed downwards with an equivalent force of 16 ounces. Now let the force upon the piston be doubled, or let the piston be loaded with a pressure of 32 ounces. The inward pressure prevailing over the elasticity, the piston will immediately be forced towards D C, but will cease to move at a certain distance A D, *fig.* 8., from the bottom. Now, if this distance A D be measured, it will be found to be exactly six inches. The air has, therefore, contracted itself into half its former dimensions.

Since the piston is sustained in the position represented in *fig.* 8., it follows that the elasticity of the air beneath it is equivalent to the weight of the piston A B; and, therefore, that the air included in the cylinder acquires double its original elasticity when it is compressed into half its original bulk.

Let the piston be now loaded with three times its original weight, or 48 ounces; it will be observed to descend into the cylinder, and further to compress the air, until its distance from the bottom is reduced to four inches. At that distance it will rest, being balanced by the increased elasticity of the air: this air

Fig. 8.



is now compressed into one third of its original bulk, and it has three times its original elastic force.

In the same manner, in whatever proportion the weight of the piston be augmented, in the same proportion will the distance from the bottom at which it will rest in equilibrium be diminished; and, consequently, the elastic force of the air is increased in the same proportion as the space into which it is compressed is diminished.

Let us again suppose the piston to be loaded with sixteen ounces, and to be balanced, as in *fig.* 7., by the resistance of the air at twelve inches from the bottom of the cylinder. But let us also suppose the cylinder continued upwards to a height exceeding 24 inches; let the weight upon the piston be now reduced to eight ounces. Since the elasticity of the air beneath the piston was capable of supporting sixteen ounces, it will now prevail against the diminished pressure of eight ounces. The piston will continue to rise in the cylinder until the elasticity of the air is so far diminished by expansion, that it is capable of supporting no more than eight

ounces; the piston will then remain in equilibrium. If the height of the piston above the bottom be now measured, it will be found to be 24 inches, that is, double its former height; the air has, therefore, expanded to double its former dimensions, and is reduced to half its former elasticity.

In like manner it may be shown, that if the weight upon the piston were reduced to four ounces, or a fourth of its original amount, the piston would rise to four times its original height, or 48 inches, before it would be capable of balancing the reduced elasticity of the air. Thus, by expanding to four times its primitive dimensions, the elasticity of the air is reduced to one fourth of its primitive amount.

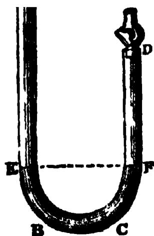
By like experiments, it is easy to see how the general law may be established. In whatever proportion the weight of the piston may be increased or diminished, in the same proportion exactly will the space filled by the air which balances it be diminished or increased.

(133.) The preceding illustration has been selected with a view rather to make the property itself intelligible, than as a practical experimental proof of it. The use of pistons moveable in cylinders is attended with inconvenience in cases of this kind, arising from the effects of friction, and the difficulties of making due allowance for them. There is, however, another method of bringing the law to the test of experiment, which is not less direct, and is more satisfactory.

Let A B C D, *fig.* 9., be a glass tube curved at one end B C, and having the short leg C D furnished with a stopcock at its extremity: let the leg B A be more than 60 inches in length. The stopcock D being opened so as to allow a free communication with the air, and the mouth A of the longer leg being also open, let as much mercury be poured into the tube as will fill the curved part B C, and rise to a small height in each leg. By the principles of hydrostatics, the surfaces of the mercury E and F will stand at the same level. Let the stopcock D be now closed, the levels E, F will still

remain undisturbed. When the stopcock D was opened the surface F sustained a pressure equal to the weight of a column of air continued from F upwards as far as the atmosphere extends. But the stopcock D being closed, the effect of the weight of all the air above that point is intercepted; and, consequently, the surface F can sustain no pressure arising from weight, except the amount of the weight of the small quantity of air included between F and D, which is altogether insignificant. But the air thus included presses on the surface F by its elasticity; and the amount of this pressure is equal to the force which confined the air within the space F D, before the stopcock was closed (131.): but this force was the weight of the column of atmosphere above D; and hence it appears, that the elastic force of the air confined in the space D F is equal to the atmospheric pressure.

Fig. 9.



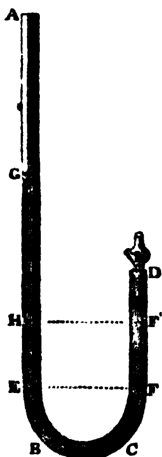
Now the other surface E, the end A of the tube being open, is subject to the atmospheric pressure. Thus the two surfaces, F and E, of the mercury, are each subject to a pressure arising from a different quality of the atmosphere; the one, F, being pressed by its elasticity, and the other, E, being pressed by its weight. These pressures being equal, the surfaces F and E continue at the same level.

The method of ascertaining, experimentally, the pressure arising from the weight of the atmosphere will be fully explained hereafter; meanwhile, it is necessary for our present purpose to assume this pressure as known. Let us suppose, then, that the atmospheric pressure acting upon the surface E is the same as would be produced by a column of mercury 30 inches in height resting on the surface E: the force with which the elasticity of the air confined in D F presses on the surface F is

therefore equal to the weight of a column of thirty inches of mercury. The pressure of the atmosphere acting on the surface E is transmitted by the mercury to the surface F, and balances the elastic force just mentioned.

Let the position of the surface F be marked upon the tube, and let mercury be poured into the longer leg at A. The increased pressure produced by the weight of this mercury will be transmitted to the surface F, and will prevail over the elasticity of the confined air: this surface will therefore rise towards D, compressing the air into a smaller space. Let the mercury continue to be poured in at A, until the surface F rise to F′, *fig.* 10., the middle point between the end D of the tube, and its first position F. The air included is thus compressed into half its former dimensions, and its elasticity will be measured by the amount of the force with which the surface A is pressed upwards against it: this force is the weight of the column of mercury in the leg B A, above the level of F′, together with the weight of the atmosphere pressing on the top G of the column. Let a horizontal line be drawn from the surface F′ to the leg B A, and let the column G H be measured; its length will be found to be accurately 30 inches, and its weight is therefore equal to the atmospheric pressure. The force with which F′ is pressed upwards is therefore equal to twice the atmospheric pressure, or to double the force with which F, in *fig.* 9., was pressed upwards. Hence it appears, that the elasticity of the air confined in the space D F′, *fig.* 10., is double its former elasticity when filling the space D F, *fig.* 9. Thus, when the air is compressed into half its volume, its elasticity is doubled.

Fig. 10.



In like manner if mercury be poured into the tube A, until the air included in the shorter leg is reduced to a third of its bulk, the compressing force will be found to be three times the atmospheric pressure, and so on.

(134.) That the elasticity of the air which surrounds us is equal to the weight of the incumbent atmosphere has been proved incidentally in the preceding experiment. Indeed, this is a proposition, the truth of which must appear evident upon the slightest consideration, and which is manifested by innumerable familiar effects. If the elastic force of the air around us were less than the weight of the incumbent atmosphere, it would yield and suffer itself to be compressed until it acquired an elastic force equal to that weight. If it were greater in amount than the weight of the incumbent atmosphere, it would overcome that weight, and would press the atmosphere upwards, until, by expanding, its elasticity were reduced to equality with the weight of the atmosphere; and these effects are continually going forward. The incumbent atmosphere is subject to continual fluctuations in weight, as will hereafter be proved; and the lowest stratum of air which surrounds us is continually undergoing corresponding contractions and expansions, ever accommodating its elasticity to the pressure which it sustains. Also this stratum of air is itself subject to changes of elasticity, from vicissitudes of temperature proceeding from the earth to which it is contiguous. These changes produce a necessity for expansion and contraction in it, even while the weight of the incumbent atmosphere remains unchanged; but the full development of this last consideration belongs to the theory of heat rather than to our present subject.

(135.) An open vessel, which is commonly said to be empty, is, in fact, filled with air; and when any solid or liquid is placed in it, so much of the air is expelled as occupied the space into which the solid or liquid entered. If such a vessel be closed by a lid or stopper, the pressure of the external atmosphere will act upon every part of the exterior surface with an intensity pro-

portionate to its weight. The air which is enclosed in the vessel will, however, act on the interior surface with an intensity proportionate to its elasticity. According to what has been already explained, this elasticity is equal to the pressure; and, therefore, there is a force tending to press the sides of the vessel outwards, exactly equal to the pressure acting on the exterior surface, and tending to press them inwards. These two forces neutralise each other, and the vessel is circumstanced exactly as if neither of them acted upon it.

When the operation and properties of some pneumatical instruments have been explained, we shall have occasion to notice many other effects of the elasticity of air.

CHAP. IV.

WEIGHT OF AIR.

MAXIM OF THE ANCIENTS. — ABHORRENCE OF A VACUUM. — SUCTION. — GALILEO'S INVESTIGATIONS. — TORRICELLI DISCOVERS THE ATMOSPHERIC PRESSURE. — THE BAROMETER. — PASCAL'S EXPERIMENT. — REQUISITES FOR A GOOD BAROMETER. — MEANS OF SECURING THEM. — DIAGONAL BAROMETER. — WHEEL BAROMETER. — VERNIER. — USES OF THE BAROMETER. — VARIATION OF ATMOSPHERIC PRESSURE. — WEATHER GLASS. — RULES IN COMMON USE ABSURD. — CORRECT RULES. — MEASUREMENT OF HEIGHTS. — PRESSURE ON BODIES. — WHY NOT APPARENT. — EFFECT OF A LEATHER SUCKER. — HOW FLIES ADHERE TO CEILINGS, AND FISHES TO ROCKS. — BREATHING. — COMMON BELLOWS. — FORGE BELLOWS. — VENT-PEG. — TEA-POT. — KETTLE. — INK-BOTTLES. — PNEUMATIC TROUGH. — GUGGLING NOISE IN DECANTING WINE.

(136.) In the history of human discovery, there are few more impressive lessons of humility than that which is to be collected from the records of the progress by which the pressure of the atmosphere which surrounds us, and the manner in which it is instrumental in producing some most ordinary phenomena, became known. Looking back from the point to which we have now attained, and observing the numerous and obvious indications of this effect which present themselves at all times, and on all occasions, nature seems almost to have courted the philosopher to the discovery. With every allowance for the feebleness of the human understanding, and for the disadvantages which the ancients laboured under, as compared with more recent investigators; still one is inclined to attribute the lateness of the discovery of the atmospheric pressure and its effects not altogether to the weakness and inadequacy of the mental powers applied to the investigation. There seems to be something of wilful perverseness and obstinacy instigating men to step aside from that course, and to turn their minds from those

instances which nature herself continually forces upon them.

The ancient philosophers observed, that in the instances which commonly fell under their notice space was always filled by a material substance. The moment a solid or a liquid was by any means removed, immediately the surrounding air rushed in and filled the place which it deserted: hence they adopted the physical dogma that *nature abhors a vacuum*. Such a proposition must be regarded as a figurative or poetical expression of a supposed law of physics, declaring it to be impossible that space could exist unoccupied by matter.

Probably one of the first ways in which the atmospheric pressure presented itself was by the effect of suction with the mouth. One end of a tube being immersed in a liquid, and the other being placed between the lips, the air was drawn from the tube by the ordinary process of inhaling. The water was immediately observed to fill the tube as the air retreated. This phenomenon was accounted for by declaring that "nature abhorred a vacuum," and that she therefore compelled the water to fill the space deserted by the air.

The effects of suction by the mouth led by a natural analogy to suction by artificial means. If a cylinder be open at both ends, and a piston playing in it air-tight be moved to the lower end, upon immersing this lower end in water, and then drawing up the piston, an unoccupied space would remain between the piston and the water. "But nature abhors such a space," said the ancients, "and therefore the water will not allow such a space to remain unoccupied: we find accordingly that as the piston rises the water follows it." By such poetical reasoning pumps of various kinds were constructed.

The antipathy entertained by nature against an empty space served the purposes of philosophy for a couple of thousand years, when it so happened that some engineers employed at Florence in sinking pumps had occasion to construct one to raise water from an unusually great depth. Upon working it they found that the water

would rise no higher than about thirty-two feet above the well. Galileo, the most celebrated philosopher of that day, was consulted in this difficulty, and, it is said, that his answer was, that "nature's abhorrence of a vacuum extended only to the height of thirty-two feet, but that beyond this her disinclination to an empty space did not extend." Some writers * deny the fact of his having given this answer; others admit it †, but take it to have been ironical. It has been more generally taken as a solution seriously intended. ‡ It appears, however, that Galileo having his attention thus directed to the point, soon saw the absurdity of the maxim, that "nature abhors a vacuum," and sought to account for the phenomenon in other ways. He attributed the elevation of the water to an attraction exerted upon that liquid by the piston. This attraction he conceived to have a determinate intensity, and when such a column of water was raised as was equal in weight to the whole amount of the attraction, then any further elevation of the water by the piston became impossible.

At a very remote period air was known to possess the quality of weight. Aristotle and other ancient philosophers expressly speak of the weight of air. The process of respiration is attributed by an ancient writer to the pressure of the atmosphere forcing air into the lungs. Galileo was, therefore, fully aware that the atmosphere possessed this property; and it is not a little surprising that when his attention was so immediately directed to one of the most striking effects of it, he was unable to perceive the connection.

Some writers § affirm, we know not upon what authority, that Galileo, at the time he was interrogated respecting the limited elevation of water in a common pump, was aware of the true cause of the effect; but that not having thoroughly investigated the subject, he evaded the question of the engineers, with a view to conceal his

* Encyclopædia Metropolitania, Pneumatics.
† Biot, Traité de Physique, tome i. p. 69.
‡ Montucla, Histoire de Mathematiques, tome ii. p. 203.
§ Biot, Traité de Physique, tome i. 69. Young's Natural Philosophy, vol. ii. p. 354.

knowledge of the principle, until he had carried his enquiry to a more satisfactory result. It does not, however, appear that he published his solution of the problem. After his death Torricelli his pupil directed his attention to the same problem. He argued that whatever be the cause which sustained a column of water in a common pump, the measure and the energy of that power must be the weight of the column of water, and, consequently, if another liquid be used, heavier or lighter, bulk for bulk, than water, then the same force must sustain a lesser or greater column of such liquid. By using a much heavier liquid, the column sustained would necessarily be much shorter, and the experiment in every way more manageable.

He therefore selected for the experiment mercury, the heaviest known liquid. The weight of mercury, bulk for bulk, being about 13½ times that of water, it follows that the height of a column of that liquid which would be sustained by a vacuum must be 13½ times less than the height of a column of water thus sustained. Hence he computed that the height of the column of mercury would be about 28 inches. He procured a glass tube, A B (*fig.* 11.), more than 30 inches in length, open at one end A, and closed at the other end B. Placing this tube in an upright position, with the open end upwards, he filled it with mercury, and applying his finger to the end A, so as to prevent the escape of the mercury, he inverted the tube, plunging the end A into a cistern C D (*fig.* 12.), containing mercury, the open end A being below the surface F of the mercury in the cistern, and no air having been allowed to communicate with it. Upon removing the finger, therefore, the mercury in the cistern came in immediate contact with the mercury in the tube. Immediately the mercury was observed to subside from the top of the tube, and its surface gradually to descend to the level E, about 28 inches above the mercury in the

Fig. 11.

A

B

cistern. This result was what Torricelli anticipated, and clearly showed the absurdity of the supposition that nature's abhorrence of a vacuum extended to the height of 32 feet. Torricelli soon perceived the true cause of this phenomenon. The atmospheric pressure acting upon the surface F, while the surface E was protected from this pressure by the closed end B of the tube, supported the weight of the column E F. This pressure was transmitted by the liquid mercury in the cistern from the external surface F to the base of the column contained in the tube.

Fig. 12.



This experiment and its explanation soon became known to philosophers in every part of Europe, and, among others, it attracted the notice of the celebrated Pascal. In order to subject the explanation of Galileo to the most severe test, Pascal proposed to transport a tube of this kind to a great elevation upon a mountain, and argued that if the cause which sustained the column in the tube were the weight of the atmosphere acting upon the external surface of the mercury in the cistern, then it must be expected that if the tube was elevated, having a less and a less quantity of atmosphere above it, the column sustained by the weight of this incumbent atmosphere must suffer a corresponding diminution in height. He accordingly directed a friend residing in the neighbourhood of a mountain, called Puys de Dome, near Auvergne, to ascend that mountain, carrying with him the apparatus already described. This was accordingly done, and the height of the column noted during the ascent. Conformably to the principle explained by Torricelli, the column was observed gradually to diminish in height, as the elevation of the apparatus was increased. The same experiment

was repeated by Pascal himself, with similar success, upon a high tower in the city of Paris.

Meanwhile other effects were manifested which not less unequivocally proved the truth of Torricelli's solution. The apparatus being kept for a length of time in a fixed position, the height of the column was observed to fluctuate from day to day between certain small limits. This effect was, of course, to be attributed to the variation of the weight of the incumbent atmosphere, arising from various meteorological causes.

(137.) The apparatus which we have just described is, in fact, the common barometer. By the principle of hydrostatics it appears, that the height of the column E F, sustained by the atmospheric pressure, will be the same, whatever be the magnitude of the bore of the tube. If we suppose the section of the bore to be equal to a square inch, then the column E F will be pressed upwards, and held in equilibrium by the weight of a column of atmosphere pressing upon a square inch of the external surface F; consequently the weight of the column E F must be equal to the weight of a column of the atmosphere whose base is a square inch, and which extends from the surface of the mercury in the cistern to the top of the atmosphere. If there be another tube whose bore is only half a square inch, then the pressure which will support the column in it will be that of a similar column of atmosphere, whose base is half a square inch; such pressure then will only be half the amount of the former, and, therefore, will only sustain half the weight of mercury. But a column of mercury of half the weight, having a base of half the magnitude, must necessarily have the same height. Hence it appears, that so long as the atmosphere presses upon a given magnitude of the surface F, with the same intensity, the column of mercury sustained in the tube will have the same height, whatever be the magnitude of its bore.

In adapting such an apparatus as this to indicate minute changes in the pressure of the atmosphere, there are many circumstances to be attended to, which we propose to explain in the present chapter, so far as they are neces-

sary to render intelligible the general principle and use of the barometer.

It is, in the first place, necessary to have the means of measuring exactly the height of the column E F, *fig.* 12.: if the surface F were fixed, and the tube B A maintained in its position, it would be sufficient to mark a graduated scale upon the tube, indicating the number of inches and fractions of an inch of any part upon it, from the surface F. But it is obvious that this will not be the case when the pressure of the atmosphere is increased, as an additional quantity of mercury is forced into the tube, and consequently an equal quantity is forced out of the cistern. While the surface E rises towards B, the surface F therefore descends, and the distance of E from that surface is increased by both causes. A graduated scale marked upon the tube would then only indicate the change in the position of the surface E, but would not show the change in the length of the column E F, so far as that change is affected by the fall of the surface F. There are several ways in which this defect may be remedied.

If the instrument be not required to give extremely accurate indications, it will be sufficient to use a tube the bore of which is small compared with the magnitude of the cistern. In this case a small change in the height of the column will make but a very inconsiderable change in the whole quantity of mercury in the cistern, and therefore will produce a very minute effect upon the position of the surface F. If such a change in the level F be so small as to affect the indications of the instruments in a degree which is unimportant for the purposes to which it is intended to be applied, the surface F may be regarded as fixed, and the whole change in the height of the column may be taken to be represented by the change in the position of the level E. All ordinary barometers are constructed in this manner.

But it is not difficult to adjust a scale upon a tube which will give with accuracy the actual variation in the length of the column by means of the change in the level of the surface E. Let us suppose that the cistern C D

has a flat horizontal bottom and perpendicular sides, and that the magnitude of the bottom bears a certain known proportion to the bore of the tube. Suppose this proportion be that of one to a hundred. If the pressure of the atmosphere increase, so as to cause the column of mercury sustained in the tube to be increased in height by one inch, then as much mercury as fills one inch of the tube will be withdrawn from the cistern ; but as the base of the cistern is one hundred times greater than the bore of the tube, it is evident that this inch of mercury in the tube would only cause a fall of the hundredth of an inch in depth of the mercury in the vessel, consequently it follows that the increased elevation of an inch in the column produces a depression of a hundredth of an inch in the surface F. Thus it appears, that the increased length of the column E F is produced by the surface F falling through the one hundredth of an inch, while the surface E rises through 99 hundredth parts of an inch. The same will be true whatever change takes place in the height of the column. We may therefore infer generally, that whatever variation may be produced in the surface E, the consequent variation produced in the height of the column is greater by a ninety-ninth part. If then the top be so graduated that a portion of it, the length of which is one hundredth part less than an inch, be marked as an inch, and all other divisions and subdivisions marked according to the same proportion, then the indications will be as accurate as if the surface F were fixed; the tube being divided accurately into inches and parts of an inch.

The barometer is represented mounted and furnished with a scale, in *fig.* 13. The glass tube is surrounded by one of brass, in which there is an aperture cut at DE, of such a length and at such a height above the cistern, as to include all that space through which the level of the mercury in the tube usually varies in the place in which the barometer is intended to be used. In these countries the level of the mercury never falls below 28 inches, nor rises above 31 inches ; consequently a space somewhat exceeding these limits will be sufficient for the

opening D E. The tube is permanently connected with the cistern A B, and a scale is engraved upon the brass tube near the aperture D E, to indicate the fractions of the height of the mercury in the tube.

Fig. 13.



There is another method of avoiding the difficulty arising from the change in the level of the surface of the mercury in the cistern, used in the barometer here represented. The bottom of the cistern moves within it in such a manner as to prevent the mercury from escaping, and a screw is inserted at V, by turning which the bottom of the cylinder is slowly elevated or depressed. An ivory index is attached to the top of the cylinder, which is presented downwards and brought to a fine point, so as to mark a fixed level. When an observation is made with the barometer, the screw V is turned until the surface is brought accurately to the point of the index, by raising or lowering the bottom according as the surface is below or above that point. It follows, therefore, that whenever an observation is made with this instrument, the surface of the mercury always stands at the same level, and therefore the divisions up on the scale C F represent the actual change of height in the barometric column.

Since the column of mercury sustained in the barometric tube is taken to represent the pressure of the atmosphere, it is clear that no air or other elastic fluid should occupy the part of the tube above the mercury. To avoid such a cause of error is not so easy or obvious as may at first appear. Mercury, as it exists in the ordinary state, frequently contains air or other elastic fluids combined with it, and which are maintained in it by the atmospheric pressure, to which it is usually subject. When it has subsided, however, in the barometric tube, it is relieved from that pressure, and the elastic force of such air as may be lodged in the mercury being relieved from the

pressure which confined it there, it will make its escape and rise to the surface, finally occupying the upper part of the tube, and exerting a pressure upon the surface of the column by means of its elasticity. Such a pressure will then assist the weight of the column of mercury in balancing the atmospheric pressure, and consequently a column of less height will balance the atmosphere than if the upper part of the tube were free from air. To remove this cause of error it is necessary to adopt means of purifying the mercury used in the barometer from all elastic fluids which may be combined with it.

The fact, that the application of heat gives energy to the elastic force of gases, enables us easily to accomplish this. For if the mercury be heated, the particles of air or other elastic fluids which are combined with it acquire such a degree of elasticity that they dilate and rise to the surface, and there escape in bubbles. The same process of heating serves to expel any liquid impurities with which the mercury may be combined. These are converted into vapour, and escape at the surface.

The presence of an elastic fluid at the top of the tube is thus removed so far as such fluids can proceed from the mercury. But it is also found that small particles of air and moisture are liable to adhere to the interior surface of the glass; and when the mercury is introduced, and a vacuum produced at the top of the tube, these particles of air dilate, and, rising, lodge at the top and vitiate the vacuum which ought to be there; the particles of moisture also evaporate and rise likewise, both producing an aeriform fluid in the chamber above the surface of the mercury, which presses upon that surface with an elastic force, and produces a corresponding diminution in the height of the column of quicksilver sustained by the atmosphere, as already explained. This imperfection may be avoided by previously heating the tube. The particles of air which adhere to its inner surface being thus expanded by heat, will fly off by their elastic force, and the particles of moisture will be converted into vapour, and likewise disengaged from the surface.

All the effects now explained may be produced by

filling the tube with mercury in the first instance, and then boiling the liquid in it, which may be easily accomplished. The heat will not only expel all liquid and gaseous impurities from the mercury itself, but also will disengage them from the inner surface of the tube. These precautions being taken, the column of mercury sustained in the tube will indicate by its weight the true amount of the atmospheric pressure. But in order to be able to compare the result of any one barometer with any other, it is necessary that the weights of equal bulks of the liquid mercury used in both cases should be the same; and for this purpose we must be assured that the mercury used is pure, and not combined with other substances. We have just seen how all substances in the liquid or gaseous form may be extracted from it. Impurities may still, however, be suspended in it in the solid form. To remove these it is only necessary to inclose the mercury in a small bag of shamois leather: upon pressing this bag the quicksilver will pass freely through its pores, and any minute solid impurities which may be contained in the mercury will remain in the bag. Pure and homogeneous mercury being thus obtained, we have advanced another step towards the certainty that the indications of different barometers may correspond; but there is still one other cause of discordance to be attended to. Suppose a barometer to be used in Paris, and another in London, at a time when the pressure of the atmosphere in both places is the same, but the temperature of the air at Paris is higher than the temperature of London. The mercury in the one barometer will have a higher temperature than the mercury in the other. Now it is well known that when mercury or any other body is heated, its dimensions increase. In other words, bulk for bulk, it become slighter. Consequently, of two columns equal in weight, that which has the higher temperature will have the greater altitude. Hence it appears, that under the circumstances supposed at a time when the atmospheric pressure is the same in London as at Paris, the barometer at the latter place will be higher

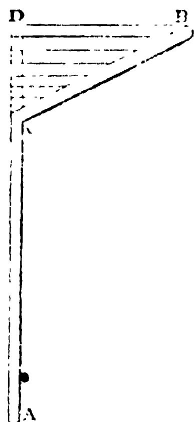
than at the former. To guard against this source of error it is necessary, in making barometric observations, to note at the same time the contemporaneous indications of the thermometer. Tables are computed showing the changes in the height of the mercury corresponding to given differences of temperature. It is evident that in comparing the results of the same barometer observed at different times, it is equally necessary to note the difference of temperature, and to allow for its effects. This, however, is a refinement of accuracy which is not attended to, except in observations made for philosophical purposes.

(138.) One of the difficulties attending barometric observations arises from the very minute changes produced in the height of the column by slight variations in the atmospheric pressure. The whole play of the upper surface of the column, in the most extreme cases, does not exceed three or four inches in a given place; and mercury being a very heavy fluid, a variation in the pressure of the atmosphere, of sensible amount, may produce scarcely any perceptible change in the height of the column. One of the most obvious remedies, at first view, would seem to be the use of a fluid lighter than mercury. In the same proportion as the fluid is lighter will the change in the height of the column by a given change in the pressure of the atmosphere be greater; but there are difficulties of a different kind which altogether preclude the use of other fluids. The lighter liquids are much more susceptible of evaporation, and the surface of the liquid in the tube being relieved from the atmospheric pressure, offers no resistance to the process of evaporation. The consequence is, that any liquid, except mercury, would produce a vapour, which, occupying the top of the tube, would press by its elastic force upon the surface and co-operate with the weight of the suspended column in balancing the atmospheric pressure. Even from mercury we have reason to know that a vapour rises which is present in the upper part of the tube, but this pressure exerts no power which can

introduce inaccuracy to any sensible extent into our conclusions.

(139.) A form is sometimes adopted, called the diagonal barometer, for the purpose of increasing the range of the mercury in the tube. This is represented in *fig.* 14., where A C B represents the barometric tube. C

Fig. 14.

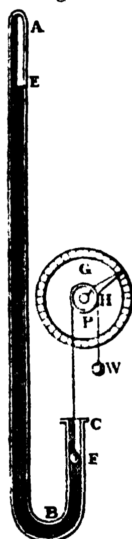


is a point at a distance above the surface of the mercury in the cylinder less than the height of 28 inches. The space C D includes the range which the mercury would have if the tube were vertical; but at C the tube is bent obliquely in the direction C B, having a sufficient length to bring the extremity B to the same level as D. The mercury which, had the tube been vertical, would range between C and D, will now have its play extended through the greater space C B; consequently the magnitude of any part, however small, will be increased in the proportion of the line C D to the line C B. Thus, if C D be 4 inches, and C B 12 inches, then every change in the position of the surface of the mercury, produced by a change in the atmospheric pressure, will be three times as

great in the diagonal barometer as it would be in the vertical one.

(140.) Another contrivance for enlarging the scale which is more frequently used, and for common domestic purposes attended with some convenience, is represented in *fig.* 15. This is called the *wheel barometer*. The barometric tube is here bent at its lower extremity B, and turned upwards towards C. The atmospheric pressure acts upon the surface F, and sustains a column of mercury in the tube B A, which is above the level of F. The bore of the tube being in this case equal in every part of its length, it is clear that through whatever space the surface E falls, the surface F will rise, and *vice versâ*. Hence it is obvious that the variation in the height of the barometric column will always be double the change in the height of either surface E or F; for if the surface F fall, the surface E must rise through the same space. They are thus receding from each other at the same rate, and therefore their mutual distance will be increased by the space through which each moves, or by double the space through which one of them moves. In the same manner, if F rise E must fall, the two points mutually approaching each other at the same rate; so that the distance between them will be diminished by the space through which each moves, or by double the space through which one of them moves. The change, therefore, in the height of the barometric column will always be double the change in the position of the level F.

Fig. 15.



Upon the surface at F there floats a small ball of iron, suspended by a string, which is carried over a pulley or small wheel at P, and counterpoised by the weight at W, less in amount than the weight of the iron ball.

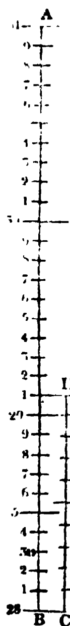
When the surface F rises, the iron ball being buoyant, will be raised with it, and the counterpoise W will fall; and when the surface F falls, the weight of the iron ball being greater than the weight of the counterpoise, will cause it to descend with the descending surface, and to draw the counterpoise W up. It is evident that, through whatever space the iron ball thus moves in ascending or descending an equal length of the string will pass over the wheel P. Now this string rests in a groove of the wheel, in such a manner that, by its friction, it causes the wheel to revolve, and, consequently, the revolution of this wheel indicates the length of string which passes over its groove, which length is equal to the change in the level of the surface F. Upon the centre of this wheel P an index H is placed, which, like the hand of a watch, plays upon a graduated circular plate. Let us suppose that the circumference of the wheel P is two inches, then one complete revolution of this wheel will correspond to a change of 2 inches in the level F, and, therefore, to a change of 4 inches in the barometric column. But in one revolution of the wheel P the hand or index H moves completely round the circle: hence the circumference of this circle corresponds to a change of 4 inches in the barometric column. Now, the circular plate may easily be made; so that its circumference shall measure 40 inches, consequently 10 inches of this circumference will correspond to 1 inch of the column, and 1 inch of the circumference will correspond to the tenth of an inch of the column. In this way variations in the height of the column amounting to the tenth of an inch are indicated by a motion of the hand H over 1 inch of the circumference of the plate. By further subdivision a still greater accuracy may be obtained.

In this form of the barometer it is evident that the preponderance of the iron ball assists the atmospheric pressure in sustaining the column. This cause of error, however, may be diminished almost indefinitely by making the preponderance of the ball over the counterpoise W barely sufficient to overcome the friction of the wheel P.

Again, when the atmosphere is diminished in weight, and when the surface F has a tendency to rise, it is compelled to raise the ball; and there is this obvious limit to the indications of the instrument, namely, that a change so slight that the difference of pressure will not exceed the force necessary to elevate the ball will fail to be indicated.

(141.) For scientific purposes, the vertical barometer is preferable to every other form of that instrument. In the oblique barometer the termination of the mercurial column is subject to some uncertainty arising from the level of the mercury not being perpendicular to the direction of the tube. In the wheel barometer there are several sources of error which, though so small in amount as not to injure it for domestic or popular use, yet are such as to render it altogether unfit for scientific enquiry. A contrivance called a Vernier, for noting extremely small changes, is usually applied to the vertical barometer, and supplies the place of an enlarged scale. It consists of a small graduated plate which is movable by a screw, or otherwise, and which slides on the divided scale of the barometer. By means of this subsidiary scale, we are enabled to estimate magnitudes on the principal scale, amounting to very small fractions of its smallest divisions.

Fig. 16.



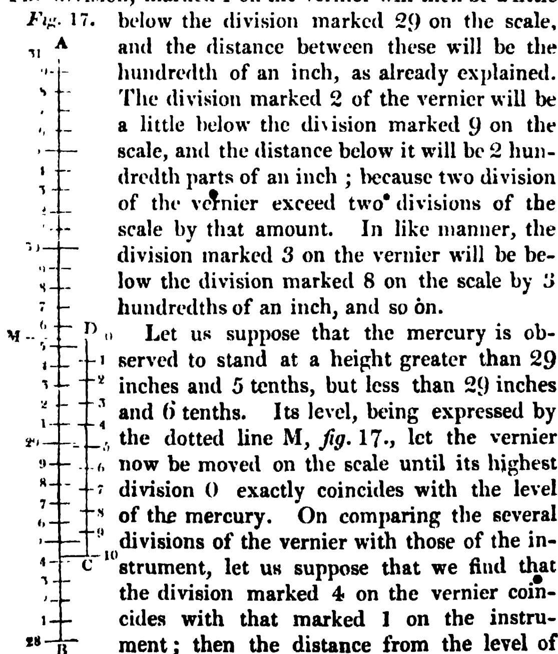
The principle of the vernier is easily explained. Let B A, *fig.* 16., represent the scale of the barometer extending through three inches and divided to tenths of an inch. Let C D be the sliding scale of the vernier, equal in length to eleven divisions of the principal scale, and divided into ten equal parts.

Thus each division of the vernier will be the tenth of eleven divisions of the instrument; that is, it will be the tenth part of 11 tenths of an inch; but 11 tenths of an inch is the same as 110 hundredths, and the tenth part of this

is 11 hundredths. Thus it appears that one division on the vernier is in this case 11 hundredth parts of an inch. Now one division on the instrument being a tenth of an inch, or 10 hundredths of an inch, it is evident that a division on the vernier will exceed a division on the instrument by the hundredth part of an inch; for if we take 10 hundredths from 11 hundredths, the remainder will be 1 hundredth.

Let us suppose that the vernier is placed so that its lowest division, marked 10, shall coincide with the lowest division on the instrument marked 28; then the first division of the vernier marked 0 will coincide with the division of the instrument next above the 29th. The division, marked 1 on the vernier will then be a little below the division marked 29 on the scale, and the distance between these will be the hundredth of an inch, as already explained. The division marked 2 of the vernier will be a little below the division marked 9 on the scale, and the distance below it will be 2 hundredth parts of an inch; because two division of the vernier exceed two divisions of the scale by that amount. In like manner, the division marked 3 on the vernier will be below the division marked 8 on the scale by 3 hundredths of an inch, and so on.

Fig. 17.



Let us suppose that the mercury is observed to stand at a height greater than 29 inches and 5 tenths, but less than 29 inches and 6 tenths. Its level, being expressed by the dotted line M, *fig.* 17., let the vernier now be moved on the scale until its highest division 0 exactly coincides with the level of the mercury. On comparing the several divisions of the vernier with those of the instrument, let us suppose that we find that the division marked 4 on the vernier coincides with that marked 1 on the instrument; then the distance from the level of

the mercury M to the next division below it marked 5 will be 4 hundredth parts of an inch; for the distance of the division marked 3 on the vernier above the division marked 2 on the instrument is 1 hundredth of an inch, because it is the difference between a division of the vernier and a division of the instrument. Again, the distance of the division of the vernier, marked 2 above the division of the instrument marked 3, is 2 hundredths of an inch, and the distance of the division of the vernier marked 1 above the division of the instrument marked 4, is 3 hundredths of an inch. In like manner the division of the vernier marked 0 is distant from the division of the instrument marked 5 by 4 hundredths of an inch. This will be manifest by considering what has been already explained. In general we are to observe what division of the vernier coincides most nearly with any division of the instrument, and the figure which marks that division of the vernier will express the number of hundredths of an inch in the distance of the level of the mercury from the next division of the instrument below it.

(142.) The most immediate use of the barometer for scientific purposes is to indicate the amount and variation of the atmospheric pressure. These variations being compared with other meteorological phenomena form the scientific data from which various atmospheric appearances and effects are to be deduced.

The fluctuations in the pressure of the atmosphere being observed in connection with changes in the state of the weather, a general correspondence is supposed to prevail between these effects. Hence the barometer has been called a *weather glass*. Rules are attempted to be established, by which, from the height of the mercury, the coming state of the weather may be predicted, and we accordingly find the words "Rain," "Fair," "Changeable," "Frost," &c., engraved on the scale attached to common domestic barometers, as if when the mercury stands at the height marked by these words the weather is always subject to the vicissitudes expressed by them.

These marks are, however, entitled to no attention; and it is only surprising to find their use continued in the present times, when knowledge is so widely diffused. They are, in fact, to be ranked scarcely above the *vox stellarum*, or astrological almanack.

It has been already explained, that in the same state of the atmosphere the height of the mercury in the barometer will be different, according to the elevation of the place in which the barometer is situated. Thus two barometers, one near the level of the river Thames, and the other on the heights of Hampstead, will differ by half an inch; the latter being half an inch lower than the former. If the words, therefore, engraved upon the plates are to be relied on, similar changes of weather could never happen at these two situations. But what is even more absurd, such a scale would inform us that the weather at the foot of a high building, such as St. Paul's, must always be different from the weather at the top of it.

The variation in the altitude of the barometer in a given place, together with the corresponding vicissitudes of the weather, have been regularly recorded for very long periods. It is by the exact comparison of such results that any general rule can be found. The rules best established by such observations are far from being either general or certain. It is observed that the changes of weather are indicated not by the actual height of the mercury but by its *change* of height. One of the most general, though not absolutely invariable, rules is, that when the mercury is very low, and therefore the atmosphere very light, high winds and storms may be expected.

The following rules may generally be relied upon, at least to a certain extent:—

1. *Generally* the rising of the mercury indicates the approach of fair weather; the falling of it shows the approach of foul weather.

2. In sultry weather the fall of the mercury indicates coming thunder. In winter, the rise of the mercury

indicates frost. In frost, its fall indicates thaw; and its rise indicates snow.

3. Whatever change of weather suddenly follows a change in the barometer may be expected to last but a short time. Thus, if fair weather follow immediately the rise of the mercury there will be very little of it; and, in the same way, if foul weather follow the fall of the mercury it will last but a short time.

4. If fair weather continue for several days, during which the mercury continually falls, a long succession of foul weather will probably ensue; and again, if foul weather continue for several days, while the mercury continually rises, a long succession of fair weather will probably succeed.

5. A fluctuating and unsettled state in the mercurial column indicates changeable weather.

The domestic barometer would become a much more useful instrument, if, instead of the words usually engraved on the plate, a short list of the best established rules, such as the above, accompanied it, which might be either engraved on the plate, or printed on a card. It would be right, however, to express the rules only with that degree of probability which observation of past phenomena has justified. There is no rule respecting these effects which will hold good with perfect certainty in every case.

(143.) One of the most important scientific uses to which the barometer has been applied is the measuring of heights. If the atmosphere, like a liquid, were incompressible, this problem would be very simple. The pressure on the mercury in the cistern would be equally diminished in ascending through equal heights. Thus, if the pressure produced by an ascent of 10 feet were equivalent to the weight of one inch of mercury, then the column would fall one inch in ascending that height. It would fall two inches in ascending 20 feet; three in ascending 30 feet, and so on. To find, therefore, the perpendicular height of the barometer at any time above its position, at any other time it would be only necessary

to observe the difference between the altitude of the mercury in both cases, and to allow 10 feet for every inch of mercury in that difference; and a similar process would be applicable if an inch of mercury corresponded to any other number of feet.

But this explanation proceeds on the supposition, that in ascending through equal heights the barometer leaves equal weights of air below it. Suppose in ascending 10 feet the mercury is observed to fall the hundredth of an inch, then it follows, that the air left below the barometer in such an ascent has a weight equal to the one hundredth of an inch of mercury. Now, in ascending the next 10 feet, the air which occupies that space having a less weight above it will be less compressed, and consequently within that height of 10 feet there will be contained a less quantity of air than was contained in the first 10 feet immediately below it. In this second ascent the mercury will, therefore, fall, not the hundredth of an inch, but a quantity as much less than the hundredth of an inch as the quantity of air contained in the second 10 feet of height is less than the quantity of air that is contained in the first 10 feet of height. In like manner in ascending the next 10 feet a still less quantity of air will be left below the instrument, and the mercury will fall in a proportionally less degree.

If the only cause affecting density of the air were the compression produced by the weight of the incumbent atmosphere, it would be easy to find the rule by which a change of altitude might be inferred from an observed change of pressure. Such a rule has been determined, and is capable of being expressed in the language of mathematics, although it is not of a nature which admits of explanation in a more elementary and popular form. But there are other causes affecting the relation of the pressure to the altitude which must be taken into account. The density of any stratum of air is not only affected by the weight of the incumbent atmosphere, but also by the temperature of the stratum itself. If any cause increase this temperature the stratum will

expand, and with a less density will support the same incumbent pressure. If, on the contrary, any cause produce a diminution of temperature, the stratum will contract and acquire a greater density under the same pressure. In the one case, therefore, a change of elevation, which would be necessary to produce a given change in the height of the barometer would be greater than that computed on theoretical principles, and in the other case the change would be less. The temperature, therefore, forms an essential element in the calculation of heights by the barometer.

A rule or formulary has been deduced, partly from established theory, and partly from observed effects, by which the change of elevation may be deduced from observations made on the barometer and thermometer. To apply that rule, it is necessary to know, 1st, the latitude of the place of observation; 2dly, the height of the barometer and thermometer at the lower station; and, 3dly, the height of the barometer and thermometer at the higher station. By arithmetical computation the difference of the levels of the two stations may then be calculated. The formulary does not admit of being explained without the use of mathematical language.

(144.) It has been already stated, that the atmospheric pressure at the surface of the earth is capable of supporting a column of water 34 feet in height. It follows, therefore, that if our atmosphere were condensed to such a degree that its specific gravity would be equal to that of water, its height would be 34 feet. Now the specific gravity of a stratum of atmosphere contiguous to the surface is about 840 times less than the specific gravity of water; that is, a cubic inch of water weighs 840 times more than a cubic inch of air. If as we ascend in the atmosphere it continued to have the same density, then its height would be evidently 840 times the height of 34 feet, which would amount to 28,560 feet, or 5 miles and a quarter. It is obvious, therefore, that since even at a small elevation the density of the atmosphere is reduced to half its density at the surface,

the whole height must be many times greater than this. The barometer in the balloon in which De Luc ascended fell to the height of 12 inches. Supposing the barometer at the surface to have stood at that time at 30 inches, it follows that he must have left three fifths of the whole atmosphere below him. His elevation was upwards of 20,000 feet.

(145.) A column of pure mercury, whose base is a square inch, and whose height is 30 inches, weighs about 15 lb. avoirdupois. It follows, therefore, that when the barometer stands at 30 inches the atmosphere exerts a pressure on each square inch of the surface of the mercury in the cistern amounting to 15 lbs. Now it is the nature of a fluid to transmit pressure equally in every direction; and if the surface on which the atmosphere acts were presented to it laterally, obliquely, or downwards, still the pressure will be the same. Taking, therefore, the medium height of the barometric column at 30 inches, it follows that the pressure sustained by all bodies which exist at the surface of the earth exposed to our atmosphere are continually under this pressure, and that every square inch on their surface constantly sustains a force of about 15 pounds. Thus, the body of a man, the surface of which amounts to 2000 square inches, will sustain a pressure from the surrounding air to the enormous amount of 30,000 pounds.

It might at first view be expected that this great force to which all bodies are subject would produce manifest effects, so as to crush, compress, or break them, whereas we find bodies of most delicate texture unaffected by it. Thus a close bag, made of the finest silver paper, and partially filled with air, is apparently subject to no external force. Its sides do not collapse. This arises partly from the circumstance of the pressure on every side, and in every direction being equal, and, therefore, producing mechanical equilibrium. It is obvious that a body which is driven in every possible direction upwards and downwards, laterally and obliquely, with equal forces, will not move in any one direction; for to

suppose such a motion would be to assume that the quantity of pressure in that direction exceeds the quantity of pressure in other directions. But still, though a body may not be driven in any direction by the atmospheric pressure, it may happen that its parts are crushed and compressed. We do not, however, find this to happen. This arises from the fact, that the elastic force of the air is equal to its pressure; and since the internal cavities of a body, such as the thin bag above mentioned, are filled with air, which is confined within them, that air has precisely the same tendency to swell the bag, and to keep the parts asunder, as the external pressure of the atmosphere has to make them collapse.

In the same manner we may account for the fact that animals move freely in the air without being sensible of the enormous pressure to which their bodies are subject. The internal parts of their bodies are filled with fluids, both in the liquid and gaseous states, which offer a pressure from within exactly equivalent to the external pressure of the air. This may be easily rendered manifest by applying to the skin the mouth of a close vessel, to which an exhausting syringe is attached. By this instrument, which will be described hereafter, the air may be rarefied in the vessel, and the atmospheric pressure consequently partially removed from the skin. Immediately the force of the fluid from within will swell the skin, and cause it to be sucked into the glass. This experiment may be performed by the mouth on the flesh of the hand or arm. If the lips be applied to the flesh, and the breath drawn in so as to produce a partial vacuum in the mouth, the skin will be drawn or sucked into the mouth. This effect is owing, not to any force resident in the lips or the mouth drawing the skin in, but to the fact that the usual external pressure is removed, and that the pressure from within is suffered to prevail.

(146.) All cases of that class of effects which are commonly expressed by the word *suction* are accounted for in the same manner.

If a flat piece of moist leather be put in close contact with a heavy body, as a stone, it will be found to adhere to it with considerable force, and if a cord of sufficient length be attached to the centre of the leather, the stone may be raised by the cord. This effect arises from the exclusion of the air between the leather and the stone. The weight of the atmosphere presses their surfaces together with a force amounting to 15 pounds on every square inch of those surfaces in contact. If the weight of the stone be less than the number of pounds which would be expressed by multiplying the number of square inches in the surfaces of contact by 15, then the stone may be raised by the leather; but if the stone exceed this weight it will not suffer itself to be elevated by these means.

The power of flies and other insects to walk on ceilings and surfaces presented downwards, or upon smooth panes of glass in an upright position is said to depend on the formation of their feet. This is such that they act in the manner above described respecting the leather attached to a stone; the feet, in fact, act as suckers, excluding the air between them and the surface with which they are in contact, and the atmospheric pressure keeps the animal in its position. In the same manner the hydrostatic pressure attaches fishes to rocks.

The pressure and elasticity of the air are both exercised in the act of breathing. When we draw in the breath we first make an enlarged space in the chest. The pressure of the external atmosphere then forces air into this space so as to fill it. By a muscular action the lungs are next compressed so as to give this air a greater elasticity than the pressure of the external atmosphere. By the excess of this elasticity it is propelled, and escapes by the mouth and nose. It is obvious, therefore, that the air enters the lungs not by any direct act of these upon it, but by the weight of the atmosphere forcing it into an empty space, and that it is expired by the action of the lungs in compressing it.

The action of common bellows is precisely similar,

except that the aperture at which the air is drawn in is different from that at which it is expelled. In the lower board of the bellows is a hole covered by a valve, consisting of a flat piece of stiff leather, movable on a hinge, and which lies on the hole, but is capable of being raised by a slight pressure. When the upper board of the bellows is raised, the internal cavity is suddenly enlarged, and the air contained in it is considerably rarefied. The pressure of the atmosphere forces in air at the nozle, but this being two small to allow its admission with sufficient ease and speed, the valve covering the hole is acted upon by the atmosphere and raised, and air rushes in through the large aperture under it. When the space between the boards is filled with air in its common state, the upper board is depressed, and the air confined in the bellows is suddenly condensed. The valve covering the hole is thus kept firmly closed, and the air has no escape except through the nozle, from which it issues with a force proportional to the pressure exerted on the upper board. A bellows, such as that in common domestic use, thus simply constructed, has an intermitting action, and blows by fits, its actior being suspended while the upper board is being raised. In forges and large factories, in which fires are extensively used, it is found necessary to command a constant and unremitting stream of air, which may be conducted through the fuel so as to keep it in vivid combustion. This is effected by bellows with three boards, the centre board being fixed and furnished with a valve opening upwards, the lower board being movable with a valve also opening upwards, and the upper board being under a continual pressure by weights acting upon it. When the lower board is let down, so that the chamber between it and the middle board is enlarged, the air included between these boards being rarefied, the external pressure of the atmosphere will open the valve in the lower board, and the chamber between the lower and middle boards will be filled with air in its common state. The lower board is now raised by the power which works the bellows,

and the air between it and the middle board is condensed. It cannot escape through the lower valve, because it opens upwards. It acts, therefore, with a pressure proportional to the working power on the valve in the middle board, and it forces open this valve, which opens upwards. The air is thus driven from between the lower and middle boards into the chamber between the middle and upper boards. It cannot return from this chamber, because the valve in the middle board opens upwards. The upper board being loaded with weights, it will be condensed while included in this chamber, and will issue from the nozle with a force proportionate to the weights. While the air is thus rushing from the nozle the lower board is let down and again drawn up, and a fresh supply of air is brought into the chamber between the upper and middle board. This air is introduced between the middle and upper board before the former supply has been exhausted, and by working the bellows with sufficient speed a large quantity of air will be collected in the upper chamber, so that the weights on the upper board will force a continual stream of air through the nozle.

The effect produced by a vent-peg in a cask of liquid depends on the atmospheric pressure. If the vent-peg stop the hole in the top while the liquid is discharged by the cock below, a space will remain at the top of the barrel in which the air originally confined is allowed to expand and become rarefied: its pressure on the surface of the liquid above will, therefore, be less than the atmospheric pressure resisting the escape of the liquid at the cock; but still the weight of the liquid itself, pressing downwards towards the cock, will cause the discharge to continue until the rarefaction of the air becomes so great, that the excess of the atmospheric pressure is more than sufficient to resist the escape of the liquid; the flow from the cock will therefore be stopped. If the vent-peg be now removed from the hole, air will be heard to rush in with considerable force and fill the space above the liquid. The atmospheric pressure on the surface

above and on the mouth of the cock being now equal, the liquid will escape from the cock by the effect of the pressure of the superior column, according to the principles established in hydrostatics. If the vent-peg be again placed in the hole, the flow from the cock will be gradually diminished, and will at length cease. Upon the removal of the vent-peg, the same effect will be observed as before.

If the lid of a tea-pot be perfectly close, and fit the mouth air-tight, or if the interstices, as frequently happens, be stopped by the liquid which lies round the edge of the mouth, then all communication between the surface of the liquid in the vessel and the external air is cut off. If we now attempt to pour liquid from the tea-pot, it will flow at first, but will immediately cease. In this case the air under the lid becomes rarefied, and the pressure on the surface of the liquid in the tea-pot is so far diminished, that the atmospheric pressure resists its discharge at the spout.

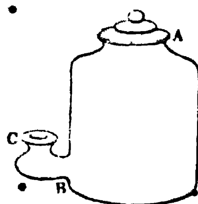
To remedy this inconvenience, it is usual to make a small hole somewhere in the lid of the tea-pot for the admission of air; this hole serves the same purpose as the hole for the vent-peg in the cask.

Although it is not usually practised, a small hole should be made in the lid of a kettle, but for a different reason. If the lid of a kettle fit it closely, so as to stop all communication between the external air and the interior of the vessel, when the water contained in it becomes heated steam will rise from its surface, and the air enclosed in the space between the surface and the lid being heated, will acquire an increased elastic force. From these causes, the pressure which acts on the surface of the water in the kettle will continually increase, so long as the lid maintains its position: this pressure, transmitted by the water in the kettle, will overcome the pressure of the atmosphere acting on the water in the spout, and the effect will be that the water will be raised in the spout and flow from it; or, if the lid be not firmly enough fixed to withstand the pressure of the steam, it will be

blown off the kettle. Such effects fall within every one's experience. If a small hole were made in the lid these effects would be prevented.

Ink bottles, constructed so as to prevent the inconvenience of the ink thickening and drying, owe their efficacy to the atmospheric pressure. The quantity of evaporation which takes place in the liquid, other circumstances being the same, is proportional to the quantity of surface exposed to the external air. To diminish this quantity of surface without inconveniently diminishing the quantity of ink in the bottle, bottles have been constructed of the shape represented in *fig.* 18.

Fig. 18.



A B is a close glass vessel, from the bottom of which a short tube B proceeds, from which another short tube rises perpendicularly. The depth of the tube C is such as will be sufficient for the immersion of a pen. When ink is poured in at C, the bottle, being placed in an inclined position, is gradually filled up to the knob A: if the bottle be now placed in the position represented in the figure, the chamber A B being filled with the liquid, the air will be excluded from it, and the pressure tending to force the ink upwards in the short tube C will be equal to the weight of the column of ink, the height of which is equal to the depth of the ink in the bottle A B, and the base of which is equal to the section of the tube C. This will be manifest from the properties of hydrostatic pressure established in Hydrostatics, chap. iii. Now the atmospheric pressure acts on the surface C with a force which would be capable of sustaining a column of ink

many times the height of the bottle A B; consequently, this pressure will effectually resist the escape of the ink from the mouth C, and will keep it suspended in the bottle A B. In this case the whole surface, which is exposed to the effect of evaporation, is the surface of liquid in the tube C; and, consequently, an ink bottle of this kind may be left many months in a warm room, and no perceptible diminution in the quantity of ink or change in its quality will take place. As the ink in the short tube C is consumed by use, its surface will fall to a level with the tube B. A small bubble of air will then insinuate itself through the tube B, and will rise to the top of the bottle A B; there it will exert an elastic pressure, which will cause the surface in C to rise a little higher, and this effect will be continually repeated until all the ink in the bottle has been used.

The only inconvenience which has been attributed to these ink bottles arises from sudden changes in the temperature to which they are exposed. When the external air, having been previously warm, becomes suddenly cool, the small quantity of air which is included in the bottle A, not being cooled so fast as the external air, will exert an elastic pressure which will cause the ink to overflow at C. This is an effect, however, which we have never observed, although we have seen these bottles much used.

If such an ink bottle be placed upon a marble chimney piece, or any other surface heated beyond the temperature of the air in the room, the air confined in the bottle will then become heated, and acquire increased elastic force, and, in this case, the ink will overflow.

The fountains for supplying water to bird cages are constructed upon the same principle.

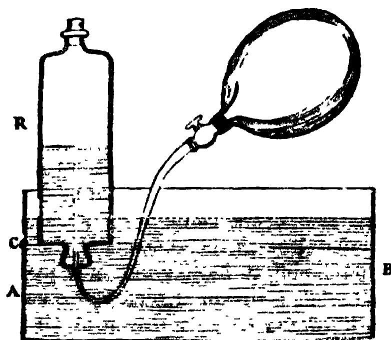
The pneumatic trough used in the chemical laboratory, and the gas holders, or gasometers, used in gas works, depend on the atmospheric pressure. A vessel, having its mouth upwards, is completely filled with a liquid. The mouth is then stopped, a flat piece of glass, or a smooth plate of metal, pressed against it, and the

vessel is inverted, the mouth being plunged in a cistern filled with the same liquid. If the height of the vessel in this case be less than the height of the column of the liquid which the atmospheric pressure would support, the vessel will continue to be completely filled with the liquid, even after the plate is removed from its mouth; for the atmospheric pressure acting on the surface of the liquid in the cistern will prevent the liquid contained in the vessel from falling out of it. Any one may satisfy himself of this fact. Take a wine glass, and fill it with water, and then having applied a piece of card to its mouth so as to prevent the water from escaping, invert it, and plunge the mouth downwards in a basin of water. Let the card be then removed, and let the glass be raised above the surface, still, however, keeping the edge of its mouth below the surface. It will be observed that the glass will still remain completely filled with water. Take a small quill, or a hollow piece of straw, and insert one end in the water, so that it will be immediately below the mouth of the glass, and at the same time blow gently through the other end, so as to introduce air in small quantities into the water immediately under the mouth of the glass. This air will ascend in bubbles, and will find its way to the highest part of the glass, and, remaining there, will expel the water from it; and this will continue so long as air is supplied, until all the water contained in the glass is expelled from it, and the glass is filled with air. If the process be further continued, the air will begin to escape under the edge of the glass, and rise in bubbles to the surface.

The pneumatic trough is a large cistern filled with mercury, in which is placed below the surface of the liquid a shelf to support a receiver. By plunging any vessel in the deeper part of the trough, it may be filled with mercury, and if it be slowly raised, keeping its mouth still below the surface of the liquid, it will still remain filled with mercury by the pressure of the atmosphere acting on the surface of the mercury in the trough. The mouth of the vessel may then be placed on

the shelf, while the vessel itself is above the surface of the mercury. The trough is represented in *fig.* 19. at

Fig. 19.



A B. The shelf is placed in it at C; a receiver R is placed on the shelf, with its mouth downwards, over an aperture D, which communicates with a tube, by which gas may be introduced. The gas passing through the tube rises in bubbles through the mercury in the receiver, and lodges at the top; and, by continuing this process, the whole of the mercury will at length be expelled from the receiver, and its place filled with the gas. In this manner gases of various kinds may be preserved out of contact with the atmosphere, and the same shelf may be furnished with several holes, and may support a number of different jars.

The gasometer used in gas works is constructed on the same principles, only on a different scale. When used for great supplies of gas, such as are necessary for the illumination of towns, these vessels are constructed of a very large size, and are immersed in pits lined with cast iron, and filled with water. It is clear that all which has been just explained will be equally applicable, whatever be the liquid used in the cistern; and for different gases it is necessary to use different liquids, since the

contact with particular liquids will frequently affect the quality of the gas.

The peculiar guggling noise which is produced in decanting wine arises from the pressure of the atmosphere forcing air into the interior of the bottle. In the first instance, the neck of the bottle is completely filled with liquid, so as to stop the admission of air. When a part of the wine has flowed out, and an empty space is formed within the bottle, the atmospheric pressure forces in a bubble of air through the liquid in the neck, which, by rushing suddenly into the interior of the bottle, produces the sound alluded to. This effect is continually repeated so long as the neck of the bottle continues to be choked with the liquid. But as the contents of the bottle are discharged, the liquid, in flowing out, only partially fills the neck, and while a stream of wine passes out through the lower half of the neck, a stream of air passes in through the upper part. The flow in this case being continual and uninterrupted, no sound takes place.

The atmospheric pressure acting on the surface of liquids maintains air combined with them in a greater or lesser quantity, according to the nature of the liquid. If an open vessel, containing a liquid, be placed under a receiver, and the air be exhausted, the air combined with the liquid will be immediately set free, and will be observed to rise in bubbles to the top. This effect will be very perceptible if water be used, but still more so in the case of beer or ale.

When liquor is bottled, the air confined under the cork is condensed, and exerts upon the surface a pressure greater than that of the atmosphere. This has the effect of holding in combination with the liquor air, which under the atmospheric pressure only would escape. If any air rise from the liquor after being bottled, it causes a still greater condensation, and an increased pressure above its surface.

If the nature of the liquor be such as to produce air in considerable quantity, this condensation will at length become so great as to force out the cork; or failing to

do that, break the bottle. This is found to happen frequently with beer, ale, or porter. The corks in such cases are tied down by cord or wire.

When the cork is drawn from a bottle containing liquor of this kind, the fixed air being relieved from the pressure of the air which was condensed under the cork instantly makes its escape, and, rising in bubbles, produces effervescence and froth. Hence the head observed on porter and similar liquors, and the sparkling of champagne or cider.

CHAP. V.

RAREFACTION AND CONDENSATION OF AIR.

EXHAUSTING SYRINGE. — RATE OF EXHAUSTION. — IMPOSSIBLE TO PRODUCE A PERFECT VACUUM. — MECHANICAL DEFECTS. — THE AIR PUMP. — BAROMETER GAUGE. — SYPHON GAUGE. — VARIOUS FORMS OF AIR PUMP. — PUMP WITHOUT SUCTION VALVE. — EXPERIMENTS WITH AIR PUMP. — BLADDER BURST BY ATMOSPHERIC PRESSURE. — BLADDER BURST BY ELASTICITY OF AIR. — DRIED FRUIT INFLATED BY FIXED AIR. — FLACCID BLADDER SWELLS BY EXPANSION. — WATER RAISED BY ELASTIC FORCE. — A PUMP CANNOT ACT IN THE ABSENCE OF ATMOSPHERIC PRESSURE. — SUCTION CEASES WHEN THIS PRESSURE IS REMOVED. — THE MAGDEBURG HEMISPHERES. — GUINEA AND FEATHER EXPERIMENT. — CUPPING. — EFFERVESCING LIQUORS. — SPARKLING OF CHAMPAGNE, ETC. — PRESENCE OF AIR NECESSARY FOR THE TRANSMISSION OF SOUND. — THE CONDENSING SYRINGE. — THE CONDENSOR.

(147.) When a part of the air enclosed in any vessel is withdrawn, that which remains expanding by its elastic property fills the dimensions of the vessel as effectually as before. Under these circumstances, however, it is obvious that any given space within the vessel contains a less quantity of air than it did previously, inasmuch as while the whole dimensions of a vessel remain the *same* the total quantity of air diffused through them is diminished. When the same quantity of air in this manner is caused to expand into a greater space it is said to be *rarefied*.

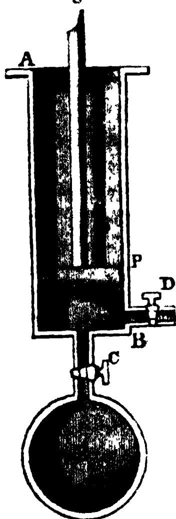
But, on the other hand, when a vessel containing any quantity of air is caused to receive an increased quantity, by additional air being forced into it, then any given portion of its dimensions will contain a proportionally greater quantity of air than it did before the additional air had been forced in. Under these circumstances, the air contained in the vessel is said to be *condensed*, and it is our purpose in the present chapter to describe the me-

chanical instruments by which these processes of *rarefaction* and *condensation* are practically effected.

The exhausting Syringe.

(148.) The most simple form of instrument for producing the rarefaction of air is that which is called *the exhausting syringe.* In order to comprehend the construction and operation of this instrument, let us suppose A B, *fig.* 20., a cylinder, or barrel, furnished with a stopcock C, inserted in a small aperture in the bottom. Let the end of this tube be screwed upon the vessel R, in which the rarefaction is to be made.

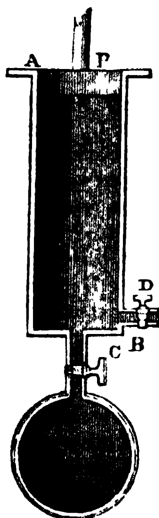
Fig. 20.



From the side of the barrel near the bottom let another tube D proceed, also furnished with a stopcock. Let us suppose the piston P at the bottom of the barrel, both stopcocks being closed. Let the piston P be now drawn from the bottom to the top, as represented in *fig.* 21., this piston being supposed to move air-tight in the barrel. A vacuum will remain between the piston P and the bottom B. If the stopcock C be opened, the air contained in the vessel R will, by its elastic force, rush through the open stopcock C, and expand so as to fill the barrel. Thus the air which previously occupied the dimensions of the vessel R has now expanded through the dimensions of R and A B. Let the stopcock C be now closed and the stopcock D opened, and let the piston P be pressed to the bottom of the barrel. The air contained in the barrel will thus be forced out at the open stopcock D, and driven into external atmosphere. Let the stopcock D be next closed, and the piston again elevated, as in *fig.* 21. A vacuum will once more be pro-

duced in the barrel; and, on opening the stopcock C, the air in R will again expand into the barrel, occupying the extended dimensions as before. Let the stopcock C be again closed, and the stopcock D opened. If the piston be pressed to the bottom of the barrel as before, the air contained in the cylinder will again be expelled through the stopcock D. By continuing this process, alternately opening and closing the two stopcocks, and elevating and depressing the piston, a quantity of air will rush from the vessel R on each ascent of the piston, and the same quantity will be expelled through the tube D on each descent of the piston.

Fig. 21.



It is evident that this process may be continued so long as the air which remains in R is capable of expanding, by its elasticity, through the open tube C into the barrel above.

A slight degree of attention only is necessary to perceive that the quantity of air expelled from R at each ascent of the piston is continually diminished; and it will not be difficult even to explain the exact rate at which this diminution proceeds. Let us suppose the magnitude of the barrel A B to have any given proportion to the dimensions of the vessel R; suppose, for example, that the dimensions of the barrel are the ninth part of those of the vessel. When the piston is first raised from the bottom to the top, the air which previously occupied the vessel expands so as to occupy the dimensions of the vessel and barrel together. The barrel, therefore, will contain a tenth part of the whole of the enclosed air; for since the vessel R contains nine times as much as the barrel, the vessel and barrel together contain ten times as much as the barrel. Consequently the tar enclosed in the barrel will necessarily be a tenth of

the whole. On depressing the piston, this tenth part is expelled through the tube D. On elevating the piston, the air remaining in the vessel R, which is nine tenths of the original quantity, now expands through the vessel and barrel, and, for the reason already assigned, the barrel will contain a tenth part of this remaining 9 tenths; that is, it will contain 9 hundredth parts of the original quantity. On the second descent of the piston, this 9 hundredth parts will be expelled. The 9 tenths which remain in the cylinder after the first stroke of the piston have now lost 9 hundredth parts of the whole; and, since 9 tenths is the same as 90 hundredths, 9 hundredths being deducted from that leave a remainder of 81 hundredths.

This, therefore, is the proportion of the original quantity which now remains in the vessel R. When the piston is next raised, this portion will expand, as before, into the enlarged space, and the tenth part of it will rise into the barrel. But a tenth part of 81 hundredths is 81 thousandths. Accordingly, on the next descent, this 81 thousandths will be expelled. The 81 hundredths which remained in the vessel R before this diminution are thus diminished by 81 thousandths. This 81 hundredths are equivalent to 810 thousandths, and, therefore, the quantity remaining in the vessel R will be found by subtracting 81 thousandths from 810 thousandths. The remainder will, therefore, be 729 thousandths, which will be the proportion of the original quantity of air which remains in the vessel after the third stroke of the piston. It will not be difficult to continue this reasoning further, and to discover not only the quantity of air expelled at each successive stroke but also the quantity remaining in the vessel R; and we may, without difficulty, compute the following table:—

Number of Strokes.	Proportion of the original quantity of air expelled at each stroke.	Proportion of the original quantity of air remaining after each stroke.	Total quantity of air expelled.
1	$\frac{1}{10}$	$\frac{9}{10}$	$\frac{1}{10}$
2	$\frac{9}{100}$	$\frac{81}{100}$	$\frac{19}{100}$
3	$\frac{81}{1,000}$	$\frac{729}{1,000}$	$\frac{271}{1,000}$
4	$\frac{729}{10,000}$	$\frac{6,491}{10,000}$	$\frac{3,509}{10,000}$
5	$\frac{6,491}{100,000}$	$\frac{58,419}{100,000}$	$\frac{41,581}{100,000}$
6	$\frac{58,419}{1,000,000}$	$\frac{525,771}{1,000,000}$	$\frac{474,229}{1,000,000}$
7	$\frac{52,771}{10,000,000}$	$\frac{4,731,939}{10,000,000}$	$\frac{5,268,061}{10,000,000}$

To make this table more intelligible, let us suppose that the vessel R contains, in the first instance, 10,000,000 grains of air. The first stroke of the piston expels a tenth part of this quantity, that is, 1,000,000 grains. There remain in the vessel R 9,000,000 grains. The tenth part of this 9,000,000 is expelled by the second stroke, that is, 900,000 grains of air. There now remain in the vessel 8,100,000 grains. Of this again a tenth part is expelled by the third stroke, that is, 810,000 grains. The quantity remaining in the receiver will then be 7,290,000 grains. The tenth part of this is expelled by the fourth stroke, that is, 729,000 grains, and there remain in the vessel 6,491,000 grains. The fifth stroke expels a tenth part of this, or 649,100 grains, and there then remain in the vessel 5,841,900 grains. A tenth part of this again is expelled by the sixth stroke, that is, 584,190 grains, and the remainder in the vessel is 525,710 grains. A tenth of this again, or 525,771

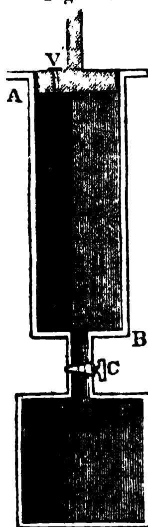
grains, is expelled by the seventh stroke. The following table exhibits these results:—

Number of Strokes.	Grains expelled at each stroke	Grains remaining under pressure.	Total number of grains expelled.
1	1,000,000	9,000,000	1,000,000
2	900,000	8,100,000	1,900,000
3	810,000	7,290,000	2,710,000
4	729,000	6,491,000	3,439,000
5	649,100	5,841,900	4,158,100
6	584,190	5,257,710	4,742,290
7	525,771	4,731,939	5,268,061

By attending to the numbers in the third column of the above table it will be perceived, that each succeeding number is nine tenths of the preceding one. It follows, therefore, that after each stroke of the piston, the quantity of air which remains in the vessel R will be nine tenths of the quantity which it contained before the stroke. From a due consideration of this circumstance, it will be perceived that however long the process of rarefaction be continued the vessel R can never be completely exhausted of air; for a determinate quantity being contained in it, nine tenths of this will remain after the first stroke. After the second stroke, nine tenths of this again will remain, and however long the operation be continued, still a determinate quantity will remain after every succeeding stroke of the piston, this quantity being nine tenths of what the vessel R contained after the preceding stroke. But although a perfect exhaustion can never be attained by these means, yet if the instru-

ment now described could be constructed as perfect in practice as it is in theory, there would be no limit whatever to the degree to which the air in the vessel R might be rarefied. Thus, by a determinate and finite number of descents of the piston, it might be reduced in weight to the millionth part of a grain, or even to a quantity millions of times less than this. Still, however small the quantity which may remain in the vessel R, so long as the elastic force by which the particles repel each other exceeds the weight of the final or ultimate particles of the air, so long that repulsive energy will cause it to expand through the tube C into the cylinder A B.*

Fig. 22.



The exhausting syringe used in practice, differs in some particulars from that which we have here described with a view to illustrate the principle of its operation. The stopcocks C and D, which would require constant manipulation while the process of rarefaction is going forward, are dispensed with in practice, and the elastic pressure of the air itself is made to act upon valves which serve the purposes of these cocks. Let A B, (*fig.* 22.) represent an exhausting syringe, having a tube and stopcock C proceeding from the lower part as already described. The tube C is screwed to a very small aperture in the bottom of the barrel. Across this aperture is stretched a small piece of oiled silk, which is impervious to air. It is extended across the aperture so loosely, that a slight pressure from below will produce an open space between it and the surface of the bottom near the aperture, capable of admitting air from below, and yet so tight that a pressure from

* If the quantity of air in the vessel R at the commencement of the process be expressed by 1, then the quantity after one stroke of the piston will be $(\frac{9}{10})$, after *two* strokes $(\frac{9}{10})^2$, after *three* strokes $(\frac{9}{10})^3$, and after *n* strokes $(\frac{9}{10})^n$.

above will cause it to lie close against the bottom, round the aperture, so as to stop the passage of air from above.

By this arrangement it is possible for air pressed with a sufficient force to enter the barrel through the valve V, when the stopcock C is opened; but it is impossible, on the other hand, for air pressing above the valve to escape through it, since the pressure of the air only serves to render more close the contact between the valve and the surface surrounding the aperture which it covers. A small hole is pierced through the piston, extending from the lower to the upper surface, and this hole at the upper surface is covered with an oiled silk valve V′, in the same manner as the aperture V in the bottom. For the reasons already assigned it is, therefore, possible for air to pass up through this hole in the piston, and escape at the upper surface; but it is impossible for air, by any pressure, to pass in the contrary direction, since such pressure only renders the contact of the valve more intimate, and consequently causes it to be more impervious to air.

Let us suppose an instrument thus constructed to be attached to a vessel R, in which the rarefaction is to be produced, and the stopcock C to be opened. On raising the piston P a vacuum will be produced between it and the valve V. The piston valve V′ will now be pressed downwards by the weight of the atmosphere, and will be subject to no pressure from below, because of the absence of air beneath it. It will then stop the admission of air from above the aperture, and will maintain the vacuum below. The elastic force of the air contained in the vessel R now acting upwards against the exhausting valve V will raise it, and the air will escape through the space between it and the surface surrounding the aperture, and will thus fill the barrel above; but the air having expanded into an increased space will have an elastic force less than that of the external air, and consequently the piston valve V′ will be pressed down, by a greater force than it is pressed up, and will therefore remain closed. Let the piston be now depressed: as it descends

the air enclosed in the cylinder acquires increased elastic force, and pressing upon the exhausting valve V causes it to close, so as to intercept the air in the cylinder from the vessel R. When the piston has descended in the barrel through such a space as to condense the air beneath it, so as to give it a greater elastic force than the external atmosphere, it will press the piston valve V′ upwards, with a greater force than the external air presses it downwards. Consequently the valve V′ will be opened, and the air confined beneath the piston will begin to escape through it. When the piston has arrived at the bottom of the barrel, the whole of the air will thus be expelled. This process is repeated whenever the piston is raised and depressed; and thus the valves, which in the form adopted for explanation required constant manipulation, acquire a self-acting property. This form of the instrument, which is that commonly used, is attended with an obvious limit to its operation, which does not exist in the theoretical form represented in *fig.* 20. It is evident that the operation of the valves depend upon the presence of air of a certain determinate elastic force in the vessel R, which elastic force it is the purpose of the instrument to reduce indefinitely. When the elastic force of the air contained in R is so far diminished that it is only equal to the force required to raise the valve V, the action of the machine must stop, for any further diminution would render the air confined in R unable to open the valve, and therefore no more air could pass into the barrel A B. This is a practical limit of the power of the exhausting syringe. The degree of perfection of which the instrument is susceptible, therefore, depends upon making the valve V offer as little resistance to being raised as is consistent with its being perfectly air-tight when closed.

But we have another limit to the operation of this instrument, arising from the piston valve V′. This valve is closed not only by its own tension, but also by the weight of the incumbent atmosphere above it. When the piston is depressed, the air included in the barrel

must first attain a degree of elastic force by condensation equal to the pressure of the atmosphere before it can open the valve V′. But this is not sufficient: it must acquire a further increased elastic force equal to the tension of the valve V′ over the aperture, in order to raise that valve and escape, and therefore the perfection of this valve also depends on having as little tension as is consistent with being perfectly air-tight from above.

The efficiency of the instrument will also depend upon the accuracy with which the piston fits the bottom and sides of the barrel. When the piston is depressed to the bottom, it is considered in theory to be in absolute contact so as to exclude every particle of air from the space between it and the bottom. But in practice this perfection can never be obtained. It may, however, be very accurately fitted, and the air retained between it and the bottom may be reduced almost without limit. The small hole which passes from the valve V′ to the bottom of the piston will still remain, however, and will continue to be a receptacle for air, even when the piston is in close contact with the bottom. This space, therefore, produces a defect in the machine which is not removed. If we suppose the magnitude of this hole, together with whatever space may remain unfilled between the lower surface of the piston and the bottom of the barrel, to be the ten thousandth part of a solid inch, then the valve V′ will cease to act when the air which fills the barrel, the piston being at the top, is such that if condensed into the ten thousandth part of an inch, its elastic force will exceed the atmospheric pressure by a quantity less than the force required to open the valve V′.

This source of imperfection will evidently be diminished by diminishing the depth of the aperture below the valve V′, and by increasing the size of the cylinder; for if the air in the barrel be as many times rarer than the external atmosphere, as the magnitude of the barrel is greater than the magnitude of the space below the valve V′, then this air, when condensed into that space, will exert a pressure equal to that of the atmosphere.

Suppose the barrel contains ten cubic inches of air, and that the magnitude of the hole is the hundredth part of a cubic inch, then the magnitude of the cylinder will be 1000 times the magnitude of the space which remains between the valve V′ and the bottom of the barrel, when the piston is pressed to the bottom. Consequently the process of rarefaction would be deduced until the air in the receiver would be rendered 1000 times rarer than the external atmosphere.

The vessel R being connected with a tube furnished with a stopcock C may be detached from the syringe together with the stopcock by unscrewing the tube C; and if the stopcock be previously closed, the interior of the vessel will continue to contain the rarefied air.

In various branches of physical science enquiries continually arise respecting qualities and effects of material substances, which are subject to considerable modification by the pressure or other qualities of the air which surrounds them; and it is often necessary in such investigations to discover what these qualities and effects may be, if the substances were not exposed to the mechanical pressure or other effects consequent upon the presence of the atmosphere. Although we do not possess any means of removing altogether the presence of this fluid, yet from what has been already stated it is plain that it may be so attenuated in an enclosed chamber, such as the vessel R, that these effects may be diminished in intensity to any degree which experimental enquiry may demand.

With these views it is necessary, however, not only to be able to introduce the substances which are submitted to experimental investigation into the chamber in which the rarefaction has been accomplished, but also to be able to observe them when so situated. The latter purpose could be accomplished by constructing the receptacle R of glass; but still it would be necessary to have access to the interior, and to construct it of a convenient form to receive the subjects of experiment, and even

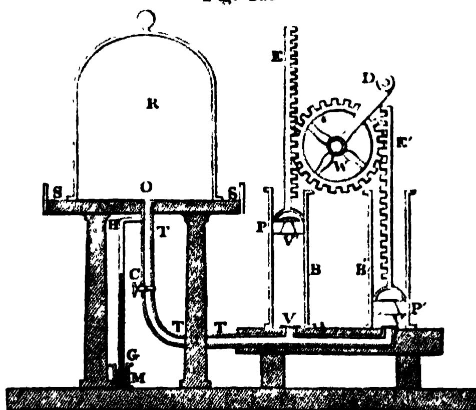
in many cases to be able to manipulate or produce changes of position on the object thus inclosed.

For these purposes the form of the vessel R, and the mode of connecting it with the syringe, must be somewhat changed, and the arrangement which is given in order to adapt them thus to all the exigencies of experimental investigation is called THE AIR PUMP, an instrument which we will now proceed to explain.

The Air Pump.

(149.) The vessel in which the rarefaction is produced by an air pump is called a *Receiver*, and is usually constructed of glass in a cylindrical form, with an arched or round top, furnished with a ball as a convenient handle. A section R of this is represented in *fig.* 23. The mouth

Fig. 23.



or lower part is open, and it is ground to a perfectly smooth and flat edge. A circular brass plate is constructed, also ground truly plane and perfectly smooth, and its magnitude is accommodated to the size of the largest receiver intended to be used; a section of this plate is represented at S S.

When the receiver is placed on the plate with its mouth downwards, the edge of the mouth and the surface of the plate should be so truly plane and smooth, that they may rest in air-tight contact. This may always be insured by smearing the ground edge of the receiver with a little lard or unctuous matter. When the receiver is thus laid on the plate it becomes an inclosed chamber, similar to R, *fig.* 22., but with this convenience, that any substance or object to be submitted to experiment may be previously placed under it, and observed through it after the air has been rarefied. In the centre of the plate S S a small aperture O communicates with a tube T, analogous to the tube inserted in the bottom of the syringe in *fig.* 22. This tube is furnished with a stopcock at C, which when closed cuts off all communication between the receiver and the syringe, and when open allows the syringe to act on the receiver as already described.

The syringe B furnished with a piston P is fixed on a firm stand, and the tube T is carried in such a direction as to open a communication with the valve V in the bottom of the syringe. To facilitate the operation, it is usual to raise and depress the piston, not by the hand applied at the extremity of the piston rod as formerly described, but by a winch D, which turns a toothed wheel W, working in corresponding teeth, formed on the edge of the piston rod E.

It is not necessary again to describe the operation of the syringe, since it is exactly what has been already explained with reference to *fig.* 22. The piston P is elevated and depressed by alternately turning the wheel W in opposite directions, and the piston valve V′ and the exhausting valve V have the property and work in the manner already described. This instrument and that represented in *fig.* 22. differ in nothing except the length and shape of the communicating tube T, the shape of the receiver R, and the mechanical method of working the piston.

To expedite the process of rarefaction, it is usual to

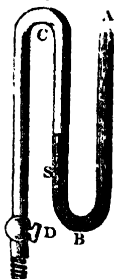
provide two syringes worked by the same wheel as represented in the figure, each being drawn up while the other is depressed. By these means a given degree of rarefaction is produced in half the time which would be required with a single syringe.

In using this instrument it is always desirable and frequently necessary to ascertain the degree of rarefaction which has been accomplished within the receiver. This is indicated, with great precision, by an apparatus called a barometric gauge, represented at H G. This consists of a glass tube H G, the upper end H of which has free communication with the receiver or rather with the tube T at some point above the stopcock C. The tube H G is more than 30 inches in length, and its lower extremity is plunged in a small cistern of mercury. As the rarefaction proceeds in the receiver, the elastic force of the air pressing upon the mercury in the tube H G is diminished, and immediately becomes less than the pressure of the external atmosphere on the surface of the mercury in the cistern M ; consequently this external pressure prevails, and forces mercury up to a certain height in the tube G H. As the rarefaction of the air in the receiver increases, its elastic force being diminished, the atmospheric pressure will prevail with increased effect, and will cause the column sustained in the tube to rise. The weight of this column, combined with the elastic pressure of the air, remaining in the receiver, is equal to the atmospheric pressure, because they are balanced by it, and it is therefore apparent that the elastic pressure of the air in the receiver must be equal to the excess of the atmospheric pressure above the weight of the mercurial column in the tube. Let us suppose that the common barometer stands at 30 inches, and that the column in the gauge measures 27 inches, the difference between these, namely, 3 inches of mercury, will express the elastic force of the rarefied air in the receiver; for the column of 30 inches in the barometer measures the atmospheric pressure, and the column of 27 inches in the gauge must be added to the pressure of the rarefied

air, in order to obtain the force which balances this pressure; therefore the force of the rarefied air must be equivalent to the pressure of 3 inches, by which the barometric column exceeds the mercurial column suspended in the gauge.

In small pumps, which are used on the table, gauges of this form are rejected in consequence of their inconvenient dimensions. An instrument called a siphon gauge is then used, the principle of which is easily understood. A small glass tube, of 8 or 10 inches in length, is bent into the form A B C D, represented in *fig.* 24. The extremity A is closed, and the extremity D opened and furnished with a screw, by which it may be attached to a tube connected with the tube T, *fig.* 23., above the stopcock C. Pure mercury is poured into the tube A B C D, *fig.* 24., until the leg A B is completely filled, and the mercury rises to S about half an inch above the inflection B. The pressure of the atmosphere communicating freely with the surface S through D C will maintain the mercury in the space S B A, and will prevent the surface S from rising towards C by the pressure of the column B A. When D is screwed to the pump and put in communication with the exhausting tube T, *fig.* 23., above the stopcock C, then the surface S will be pressed by the elastic force of the air in the receiver R, with which it communicates. So long as that elastic force is capable of sustaining the column of mercury in the leg B above the level of the surface S, this instrument will give no indication of the degree of rarefaction; but when, by the operation of the syringe, the air in the receiver is so far exhausted that its elastic force is unable to sustain the mercurial column in B A above the level S, then the mercury will begin to fall in the leg B A, and the surface S will rise in the leg B C. The column suspended in the leg B A, above the level S, will now be the exact measure of the elastic force of the

Fig. 24.



air in the receiver which sustains it. In this respect the siphon gauge must be regarded as a more direct measure of the elastic force of the air in the receiver than the barometer gauge. The latter, in fact, measures, not the elastic force of the air in the receiver, but the difference between that elastic force and the pressure of the atmosphere. To obtain the elastic force of the air in the receiver it is necessary also to ascertain the indications of the barometer. The siphon gauge, however, gives at once the pressure of the air in the receiver.

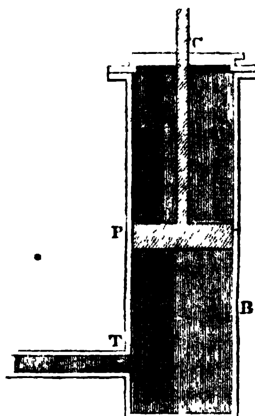
(150.) The air pump has been constructed from time to time in a great variety of forms, the details of which it would not be proper to introduce into the present treatise. The general principle in all is the same: they differ from each other chiefly in the construction of the piston and valves.

In the form which has been above described, the air effects its escape from the receiver at each stroke of the piston by opening the suction valve V, *fig.* 23. Now in whatever way this valve is constructed it must require some determinate force to raise it; and this force, in the case already described, is the elastic force of the rarefied air remaining in the receiver. Thus the operation of the machine is accomplished by the presence in the receiver of the very agent which it is the object of the machine itself to remove, and from the very construction of the instrument it must cease to act while yet air of a determinate pressure remains in the receiver.

This defect has been sometimes attempted to be removed by causing the suction valve to open, not by the pressure of the rarefied air, but by some mechanical means acted upon by the piston. Such contrivances, however, are found to be attended with peculiar inconveniences which more than outweigh their advantages. Probably the most simple and the best contrivance is one in which the suction valve is altogether dispensed with, and the air passes freely through the open tubes from the receiver to the pump barrel. Let T, *fig.* 25., be the exhausting tube which is carried from the receiver,

and enters the pump barrel at a point distant from the bottom of the barrel by a space equal to the thickness of the piston. The piston P is a solid plug, which moves

Fig. 25.



air-tight in the barrel, and is propelled by a polished cylindrical rod which slides in an air-tight collar C in the top of the cylinder, which in this case is closed. A valve is placed in the top of the cylinder, which opens outwards, and which may be constructed in the same manner as the silk valves already described. When the piston descends it leaves a vacuum above it, the external air not being allowed admission through the valve at the top; and when the piston arrives at the bottom of the barrel it has passed the mouth of the exhausting tube T, and fills the space below it. The air in the receiver then expands into the empty pump barrel, and when the piston is raised, having passed the mouth of the tube T, the air which has expanded into the barrel is confined between the piston and the top, where, as the piston rises, it is condensed. When it acquires sufficient elastic force it opens the valve at the top, and is discharged into the atmosphere.

The valve in the top of the barrel is in this case continually under the atmospheric pressure, and therefore the air confined in the pump can never be driven through it, until it is condensed by the piston, so that its force shall be greater than that of the atmosphere. From the causes already explained, arising from inaccuracy of mechanical construction, some small space must inevitably remain between the piston and the top of the barrel even when the piston is drawn upwards as far as possible. This small space will contain condensed air, and the valve at C will cease to act, when the air which occupies this space exceeds the atmospheric pressure by a force less than the tension of the valve.

When the piston is pressed to the bottom, a small space will likewise remain between the piston and the bottom, which will be occupied by air, but at each ascent of the piston this air expands, and is subject to constant diminution as the working of the pump is continued.

The principal source of imperfection in such an instrument, independently of that which arises from the mechanical inaccuracy of its construction, depends on the tension of the valve in the top, and the pressure of the atmosphere upon it. To diminish this imperfection, the valve in the top is sometimes made to communicate by a pipe with a small subsidiary exhausting syringe, by which the pressure of the atmosphere on the valve may be partially withdrawn, so that a less force acting under the valve may open it.

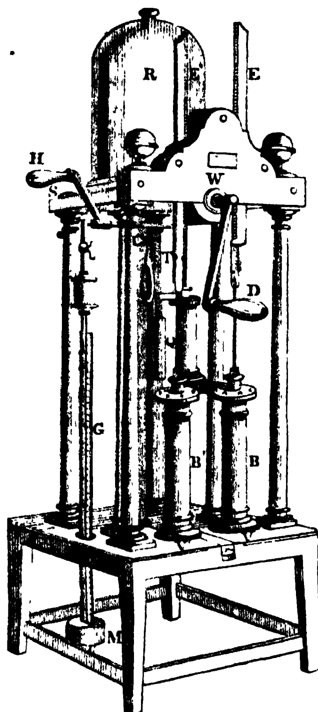
A perspective view of an air pump, with all its accompaniments, constructed upon this principle, is exhibited in *fig.* 26., where the several parts of the machine are marked with the same letters as the corresponding part in the sectional diagram, *fig.* 23. The subsidiary syringe just alluded to is also represented at Q. It is worked by a handle H.

Experiments with the Air Pump.

(151.) The pressure and elasticity of air are capable of being strikingly illustrated in various ways by experiments with the air pump.

If a glass receiver, open at both ends, have a strong bladder tied upon one end, so as to be air-tight, and be placed upon the open end on the plate of an air pump, when the air is exhausted from the receiver, the pressure

Fig. 26.



of the external atmosphere on the bladder will immediately cause its upper surface to be concave, and when the air is sufficiently rarefied within the receiver, the pressure on the bladder will burst it, producing a loud noise like the discharge of a pistol.

Again, if a large glass bowl, having a bladder tied

firmly on its mouth so as to be perfectly air-tight, be placed under the receiver of the air pump, on withdrawing the air the elastic force of the air confined in the bowl being still undiminished, and being no longer balanced by the atmospheric pressure on the outside, the bladder will be blown into a convex form; and when the air in the receiver is so rarefied that the elasticity of the air confined in the bowl suffers little resistance, the bladder will burst, and the air confined in the bowl will expand through the receiver.

(152.) Fruit when dried and shrivelled contains within it particles of air, which are held in its pores by the pressure of the external atmosphere. If, therefore, this pressure be removed, we may expect that the air thus confined will expand, and if there is no aperture in the skin of the fruit for its escape, it will distend the skin. Fruit in this case placed under a receiver will assume the appearance of ripeness by exhausting the air; for the expansion of the air contained in the fruit by inflating the skin will give it a fresh, ripe appearance. Thus a shrivelled apple will appear to grow suddenly ripe and fresh; and a bunch of raisins will be converted into a bunch of ripe grapes.

(153.) A flaccid bladder closed so as to be air-tight at the mouth contains within it a small portion of air. This air presses by its elasticity on the inner surface, which is resisted by the atmospheric pressure from without. If such a bladder be placed under the receiver of a pump and the air exhausted, the external pressure being thus removed, the elasticity of the air included will cause the bladder to swell, and it will take all the appearance of being fully inflated. Such a bladder placed under several heavy weights will raise them by the expansion of the air.



Fig. 27.

(154.) Let a close glass vessel A B, *fig.* 27., be partially filled with water, and let the tube C D be inserted through

its neck, the end D being below the surface of the water; the air above the surface will thus be confined. If such a vessel be placed under a receiver, and the air be withdrawn, the elastic force of the air confined in A B above the surface of the water will press the water up in the tube D C, from which it will issue in a stream at C, when the pressure of the atmosphere is sufficiently removed by rarefaction.

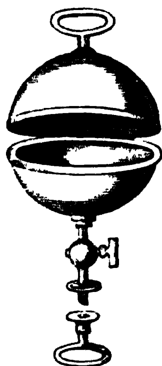
(155.) By means of an air pump we are enabled to demonstrate that the power which causes water to follow the piston in a pump is the atmospheric pressure, by showing that the water will not follow the piston when that atmospheric pressure is removed. Let a small exhausting syringe, with its lower end in a vessel of water, be placed on the plate of the air pump, and let a glass receiver, open at the top, be placed over it. On the top of this receiver let a brass cap fitting it air-tight be placed, through a hole in the centre of which a metal rod terminating in a hook passes air-tight. Let the hook be attached to the end of the piston rod, so that by drawing the rod up through the air-tight collar, the piston may be drawn from the bottom of the cylinder towards the top. If this be done before the air has been exhausted from the receiver, the water will be found to rise after the piston as in the common pump; but as soon as the air in the receiver has been highly rarefied, it will be found that although the piston may be drawn up in the syringe the water will not follow it. This effect may be rendered visible by constructing the barrel of the pump or syringe of glass, through which the water will be seen to rise in the one case and not in the other.

(156.) If an air-tight piston be placed in close contact with the bottom of a syringe not furnished with a valve, any attempt to draw it up will be resisted by the atmospheric pressure; and if it be forced to the top of the cylinder and there discharged, it will be immediately urged with considerable force to the bottom. The atmospheric pressure above the piston, acting with a force of about 15 pounds on the square inch, produces this effect;

for the space between the piston and the bottom of the cylinder not containing any air, this pressure is unresisted. Now if this piston be introduced under the receiver of an air pump, and be drawn up as already described, it will be found that in proportion as the air is withdrawn from the receiver, less and less force will be required to produce the effect; and, at length, the rarefaction will become so great, that the pressure of the remaining air is incapable of overcoming the friction of the piston with the cylinder, and it will, when drawn to the top, remain there, without returning to the bottom. In this state, let the air be re-admitted to the receiver; the piston will then be immediately pressed to the bottom of the cylinder.

(157.) The celebrated experiment of the Magdeburgh hemispheres may be performed by means of an air pump. Two hollow hemispheres, constructed of brass, as represented in *fig.* 28., are so formed that when placed mouth to mouth they shall be in air-tight contact. They are furnished with handles, one of which may be screwed off. In the neck to which this handle is screwed is a tube furnished with a stopcock. The handle being screwed off, let the hemisphere be screwed on the pump plate, and the other hemisphere being placed over it, let the stopcock be opened so as to leave a free communication between the interior of the sphere and the exhausting tube of the air pump. The pump being now worked, the interior of the sphere will form the receiver from which all communication with the external air is cut off, and rarefaction will be produced in it to any degree which may be desired. This being effected, let the stopcock be closed; and let the sphere be detached from the pump plate, and the handle screwed upon it. If then the two handles

Fig. 28.



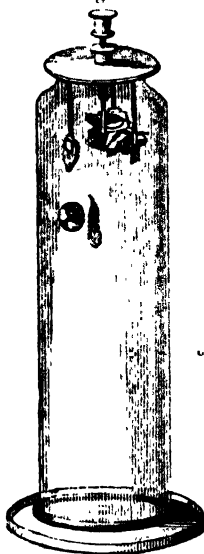
be drawn in opposite directions, so as to pull the hemispheres from one another, it will be found that they will resist with considerable force. If the diameter of the sphere be 6 inches, its section through the centre will be about 28 square inches. The hemispheres will be pressed together by a force amounting to 15 pounds for every square inch in the section. If 28 be multiplied by 15 we shall obtain 420, which is the amount of the force with which the hemispheres will be held together. If one of the handles be placed on a strong hook, and a weight of 400 pounds be suspended from the other, the weight will be supported by the pressure of the atmosphere.

This was one of the earliest experiments in which the effects of atmospheric pressure were exhibited. Otto Guericke, the inventor of the air pump, constructed, in 1654, a pair of such hemispheres one foot in diameter. The section through the centre of these was about 113 square inches, which multiplied by 15 gives a pressure amounting to about 1700 pounds. If the exhaustion were complete, the hemispheres would be held together by this force; but, even though incomplete, they were still able to resist a prodigious force tending to draw them asunder.

(158.) It is a consequence of the general theory of gravitation, that under the same circumstances, bodies are attracted in proportion to their mass; and hence it would follow, that all bodies, whatever be their masses, should fall at the same rate. Now the instances which most commonly come under our observation seem to contradict this inference; for we find a piece of metal and a piece of paper fall at very different rates, and still more different is the rate at which a piece of metal and a feather would fall. The cause of this circumstance, however, is easily explained. The resistance offered by the air is proportional to the quantity of surface which the body presents in the direction of its motion. Now the metal may present a considerably less surface than the feather, while the force which it exerts to overcome

the resistance is many times greater, because of its greater weight. Hence it follows, that the resistance of the air produces a different effect on the metal compared with the effect which it produces on the feather; but all doubt will be removed if the feather and the metal are allowed to fall in a chamber from which the air has been withdrawn. A glass receiver is represented in *fig.* 29., which

Fig. 29.



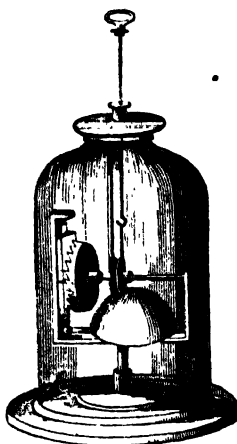
may be placed on the plate of an air pump, and on the top is placed a brass cover, which is air-tight. Under this several brass stages are attached, constructed in the manner of trap doors on the hinges, and supported by small pins, which project from the sides of a metal rod, passing through an air-tight collar in the brass cover. By turning this metal rod the pins may be removed from under the trap doors, and they will fall, disengaging whatever may be placed upon them. Suppose a piece of coin and a feather be placed upon one of these stages, supported by a projecting pin. This arrangement being made, let the brass cover be placed on the receiver, so as to be air-tight, and let the receiver be then exhausted by the pump. When a high degree of rarefaction has been produced, let the rod be turned by the handle at the top, so as to remove the pin from under the stage; the coin and the feather will be immediately let fall, and it will be observed that they will both descend at exactly the same rate, and strike the bottom at the same instant. This is the experiment commonly known by the name of "the guinea and feather experiment."

(159.) The surgical process called cupping consists in removing the atmospheric pressure from the part of

the body submitted to the operation. A vessel with an open mouth is connected with an exhausting syringe. The mouth is applied in air-tight contact with the skin, and, by working the syringe, a part of the air is withdrawn from the vessel, and, consequently, the skin within the mouth of the vessel is relieved from its pressure. All the other parts of the body, however, being still subject to the atmospheric pressure, and the elastic force of the fluids contained in the body having an equal degree of tension, that part of the skin which is thus relieved from the pressure will be swelled out, and will have the appearance of being sucked into the cupping glass. If the skin be punctured by lancets, the blood will thus be drawn from it in a peculiar manner.

(160.) That the presence of air is necessary for the transmission of sound may be strikingly illustrated by the air pump. A small apparatus, *fig.* 30., which, by

Fig. 30.



being drawn upwards and downwards alternately, causes a bell to ring, is placed on the pump plate, and covered by a receiver with an open top. A brass cover, fur-

nished with a sliding rod, is placed upon this. The sliding rod is terminated in a hook, which catches the apparatus, and by which it may be alternately raised and lowered, without allowing any air to pass into the receiver. The apparatus being thus suspended in the receiver by a silken thread, so that it shall not touch the bottom or sides, let the air be exhausted by the pump. When the rarefaction has been carried to a sufficient extent, let the rod be alternately raised and lowered, so that the bell shall ring. It will be found to be inaudible.

If the air be now gradually admitted, the sound will at first be barely audible, but will become louder by degrees, until the receiver is again filled with air, in the same state as the external atmosphere. In this experiment care must be taken not to let the sounding apparatus rest on the pump plate, for it will then communicate a vibration to that, which will finally affect the external air and produce a sound.

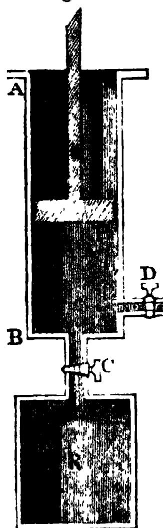
The condensing Syringe.

(162.) The condensing syringe is an instrument by which a greater quantity of air may be forced into a vessel than that vessel contains when it has a free communication with the external atmosphere.

Let A B, *fig.* 31., be a cylinder furnished with a piston P which moves air-tight in it. Let C be a tube proceeding from the bottom, and furnished with a stopcock. Let us suppose this tube to communicate with the receiver or vessel R, in which it is intended to condense the air. Let another tube D proceed from the cylinder, also furnished with a stopcock. Let the piston be now drawn to the top of the cylinder, both stopcocks being open. The receiver R being in free communication with the atmosphere, will contain air of the same density and pressure as the external atmosphere. Let the stopcock D be now closed, and let the piston be pressed to the bottom of the cylinder, the air confined in the cylinder

below the piston will thus be forced through the tube C into the vessel R, while the piston is pressed against the bottom B. Let the stopcock C be closed so as to prevent the escape of the air from the vessel R, and let the stopcock D be opened so as to allow a free communication between the cylinder A B and the external atmosphere. Let the piston be again drawn to the top of the cylinder. The cylinder will then be filled with atmospheric air of the same density as the external atmosphere. Let the stopcock D be closed and C opened, and let the piston be once more forced to the bottom of the cylinder, the contents of the cylinder will be thus again discharged, and forced into the receiver R. Let the stopcock C be again closed, and let the process be repeated. It is evident that at each stroke of the piston a volume of atmospheric air will be forced into the receiver equal to the dimensions of the cylinder A B; and there is no limit to the degree of condensation, except that which depends on the strength of the receiver R and the cylinder and tubes, and on the power by which the piston is urged.

Fig. 31.

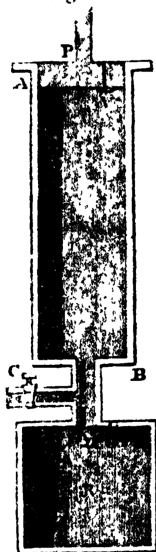


After each stroke of the piston, the density of the air in R is increased by the admission of as much atmospheric air as fills the cylinder A B, and therefore the density, as the process advances, receives equal increments at each stroke of the piston. Let us suppose that the receiver R has ten times the capacity of the cylinder A B, and let us suppose that the elastic pressure of the air in R at the commencement of the operation is expressed by the number 10. After the first stroke this pressure will be expressed by the number 11, inasmuch as the quantity of air in R has been increased by one tenth

part of its volume. After the second stroke the pressure will be expressed by the number 12. After the third by the number 13, and so on.

In the form given in practice to the condensing syringe, the necessity for manipulating by the stopcocks here represented is removed. A silk valve, such as that described in the exhausting syringe is placed in the tube C, *fig.* 32., but opening downwards. The neck of the receiver R is furnished with a stopcock and a tube, which terminates in a screw. This screw is connected with a corresponding one proceeding from the bottom of the syringe. By this arrangement, the air is capable of passing through the silk valve from the syringe to the receiver, but not in a contrary direction. A small hole is made through the piston, extending from the upper to the lower surface, and the silk valve is extended across this hole on the lower surface, so that air is capable of passing through this valve to the cylinder below it, but not in a contrary direction.

Fig. 32.



Now let us suppose that the air in the receiver has the same pressure and density as the external atmosphere, and let the piston P be at the top of the cylinder, the air in the cylinder A B also having the same pressure and density as the external air. By pressing the piston towards the bottom of the cylinder, the air enclosed will become condensed, and by its increased pressure will open the valve V, and as the piston descends will be forced into the receiver R. When the piston has arrived at the bottom, all the air contained in the cylinder will be transferred into the receiver. It will be retained there, because the valve V, opening downwards, will not permit its return. If the piston be

now drawn up it will leave a vacuum below it when it begins to ascend, but the pressure of the atmosphere above will open the valve V′, and the air rushing through will fill the cylinder as the piston ascends; and when the piston has arrived at the top of the cylinder, the space below it will again be filled with atmospheric air. By the next descent of the piston this air is forced into the receiver R as before, and so the process is continued.

It should be observed, that when the piston P is drawn to the top of the cylinder, the air which has passed into A B has not quite so great a pressure as the external atmosphere. This arises from the valve V′ requiring some definite force, however small, to open it. When the air which has passed into the chamber A B acquires a pressure which is less than the atmospheric pressure by an amount equal to the tension of the valve V′, then the excess of the pressure of the atmosphere over the resistance of the air contained in A B will be insufficient to open the valve V′, and no more air can pass into the cylinder. It should also be observed, that the valve V being pressed upwards by the elastic force of the air condensed in the receiver requires a still greater pressure than this to open it, and therefore before the valve V can be opened, the air enclosed below the piston P must always be condensed by the pressure of the piston in a higher degree than the air is condensed in the receiver. The observations which have been made respecting the limit of the operation of the exhausting syringe, arising from mechanical imperfections and other causes, will also be applicable here. However nicely the piston P, and the cylinder in which it plays, may be constructed, there will still be some small space remaining between it and the silk valve V, when it is pressed to the bottom of the cylinder. Into this space the air contained in the cylinder may, finally, be condensed; and when the pressure of the air contained in the receiver becomes equal to the pressure of the air condensed into the space between the piston at the bottom of the cylinder and the silk valve the operation of the instrument

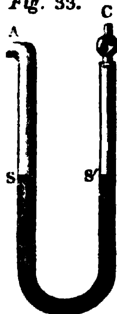
must necessarily cease; for then the utmost degree of condensation which can be produced above the silk valve V will be insufficient to open the valve, and therefore the syringe cannot introduce more air into the receiver.

The Condenser.

(163.) The condenser has the same relation to the apparatus just described, as the air pump has to the exhausting syringe. The condenser consists of a receiver firmly and conveniently fixed, communicating by a tube with one or two condensing syringes, which may be worked in the same manner as the exhausting syringe described in the air pump.

In the use of such an instrument it is convenient to possess the means of indicating the degree of condensation which has been effected. For this purpose a mercurial gauge is used analogous to that which is applied to the air pump. A bent tube, A B C, *fig.* 33., contains a small quantity of mercury, S, B, S′, in the curved part. When the ends of the tube are open, and in free communication with the atmosphere, the surfaces, S, S′, will stand at the same level. The extremity C is furnished with a stopcock, by which a communication with the atmosphere may be permitted or intercepted. The extremity A communicates by a tube with the receiver in which the air is to be condensed. At the commencement of the process, before any condensation has taken place, the stopcock C is closed, and the air included between it and the surface S′ has then the same pressure as the external atmosphere. The air in the receiver having also that pressure, the two surfaces S and S′ necessarily stand at the same level. When the condensation of air in the receiver commences the pressure on the surface S is increased, therefore that surface falls,

Fig. 33.



and the surface S′ rises. The pressure of the air condensed in the receiver will thus be balanced by the weight of the column of mercury between the levels S and S′, together with the pressure of the air inclosed between S′ and C. But by what has been proved in (133.) it follows, that the pressure of the air inclosed in S′ C is increased in the same proportion as the space S′ C has been diminished. Now, as the original pressure of the air contained in this space was equal to the pressure of the atmosphere, it is always easy to find the pressure of the air reduced in bulk by increasing the amount of atmospheric pressure in the same proportion as the space S′ C has been diminished. Thus, if the air enclosed in the tube be reduced to half its original bulk, then the pressure it exerts will be double the atmospheric pressure. If it is reduced to two thirds of its bulk, then the pressure of the enclosed air will be to the atmospheric pressure in the proportion of three to two, and so on. The pressure thus computed being added to the pressure arising from the column of mercury between the levels of the surfaces S and S′, will give the whole pressure of the air condensed in the receiver.

Although the condenser is not without its use in experimental physics, yet it is an instrument far less important than the air pump to which it is so analogous. The cases are innumerable in which it is necessary to enquire what effect would take place in the absence of the atmosphere; but they are comparatively few in which it is necessary to investigate what effects would be produced under increased atmospheric pressure.

We do not, therefore, think it necessary in a treatise of this nature to enter into further details concerning the condenser.

CHAP. VI.

MACHINES FOR RAISING WATER.

THE LIFTING PUMP. — PUMP WITHOUT FRICTION. — THE SUCTION PUMP. — THE FORCING PUMP. — THE SAME WITH AIR VESSEL. — THE SAME WITH A SOLID PLUNGER. — DOUBLE FORCING PUMP. — THE FIRE ENGINE. — SIPHONS. — THE WURTEMBURG SIPHON.

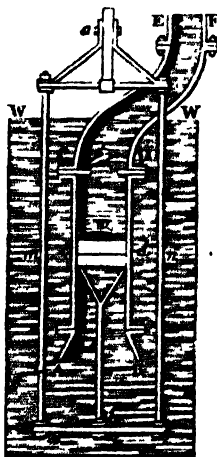
(164.) MACHINES of a great variety of forms, and constructed upon various principles, derived from mechanics, hydrostatics, and pneumatics, have been applied to the purposes of raising water above its natural level. These machines generally are called *Pumps*.

The most simple machine of this description is that which is called

The lifting Pump.

(165.) Let A B D C, *fig.* 34., be a short cylinder, submerged in the well or reservoir from which the water is to be raised. This cylinder communicates by a valve *x*, with a tube or pipe C E, which is carried upwards to whatever height it is required to raise the water. A piston moves water-tight in the cylinder A D, and is worked by a rod or framework, as represented in the figure. This piston is furnished with a valve *v*, which opens upwards.

Fig. 34.



When the piston descends, the pressure of the water opens the valve *v*, and the cylinder between the two valves is filled with water. When the piston is raised, the water between the valves

being pressed against the valve *x* opens it, and is driven into the tube C E, from which its return is intercepted by the valve *x*. The water follows the piston in its ascent by the hydrostatical pressure of the water in the reservoir outside the cylinder; and on the next descent of the piston water will again pass through the valve *v*, which will be driven through the valve *x* on its next ascent.

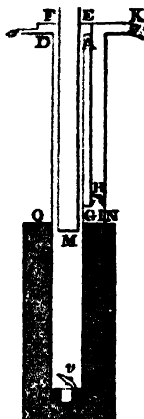
The use of the valve *x* is evidently to relieve the valve *v* during the descent of the piston from the pressure of the column of water in the tube C E. If the valve *v* were subject to that pressure, it would fail to be opened during the descent of the piston by the pressure of the water in the well, because the level of that water is necessarily below the level of the water in the pipe C E.

The use of the valve *v* is to prevent the return of the water through the piston during its ascent. In drawing up the piston a force will be necessary sufficient to support the entire column of water from the valve *v* to the surface of the water in the tube C E. The actual amount of this force is the weight of a column of water, whose base is equal to the horizontal section of the piston, and whose height is equal to the height of the surface of the water in the tube C E above the valve *v*. It is evident that after each stroke of the pump the pressure on the piston and the force necessary to raise it will be increased by the weight of a column of water whose base is the horizontal section of the piston, and whose height is equal to the increase which the elevation of the column in C E receives from the water driven through the valve *x*.

(166.) The ingenious form of pump represented in *fig.* 35. acts upon the principle of the lifting pump, though very different from it in appearance. It is recommended by the circumstance of being free from friction, or nearly so, and by being capable of being worked by the weight of an animal walking up an inclined plane, one of the most advantageous ways in which animal power can be applied.

Let A B C D be a wooden tube of any shape, round or square, which descends to a depth in the well or reservoir equal to the height above the surface of the reservoir to which the water is required to be raised.

Fig. 35.

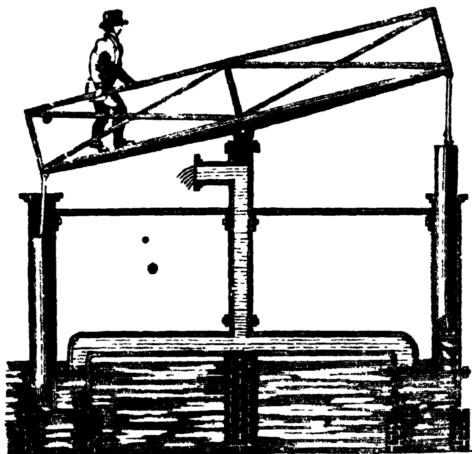


Thus if A H be the height to which the water is to be raised above the level of the well, then the depth G B must be at least equal to A H. L M is a heavy beam or plunger, suspended from a chain, and capable of descending by its own weight in water. A valve *v* covers an opening placed at the bottom of the tube or barrel. By the hydrostatic pressure the water will enter the valve *v*, and fill the barrel to the level of the water in the cistern. G I is a short tube proceeding from the side of the barrel, at the surface of the water, and communicating with the vertical tube A H by a valve H, which opens upwards. K is the spout of discharge. The plunger L M hangs loosely in the tube, so that it moves upwards and downwards perfectly free from friction. When this plunger is allowed to descend by its weight into the water which fills the lower part of the tube, the valve *v* is closed, and the water displaced by the plunger is forced through the valve H into the tube A H. When the plunger is raised the valve H is closed, and the water thus forced into the tube A H cannot return. The water from the cistern then flows through the valve *v*, and rises in the tube to the level G. The next descent of the piston propels more water into the tube A H, and this is continued so long as the piston is worked.

The manner in which such an apparatus is worked by the weight of a man is represented in *fig.* 36. Two pumps are used, such as that just described, and when the plunger descends in one it rises in the other. The

two pumps communicate with one vertical pipe, which therefore receives a continual supply of water; for while the action of one pump is suspended the other is in progress. A man walks from one end of an inclined plane

Fig. 36.



to the other, and by his weight upon one side or the other of the fulcrum causes the plungers alternately to rise and fall.

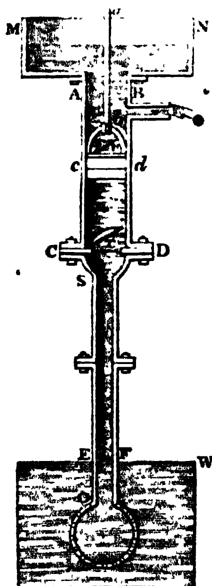
The Suction Pump.

(167.) The common suction pump is a large syringe, which is connected with a tube, the lower extremity of which is plunged in a well, from which water is to be raised. This tube is called a suction pipe.

Let W, *fig.* 37., represent the well or reservoir from which the water is to be elevated, and let S O represent the suction tube. The lower end O of this tube being pierced with holes acts as a strainer, and prevents the admission of solid impurities into the pipe which might choke the pump and impede its action. At the upper end of the suction tube a valve *x* is placed,

which opens upwards, and at this point the tube is connected with the great syringe B C, furnished with a piston, in which there is another valve *v*, which also opens upwards, as already described in the exhausting syringe. The piston is worked alternately upwards and downwards in common pumps by a lever, called the brake, but may also be worked in many other ways. At the commencement of the operation, the level of the water in the suction tube coincides with the level of

Fig. 37.



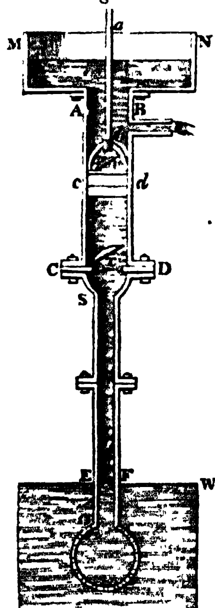
the external water in the well, because both are subject to the same atmospheric pressure; but when the syringe B C is worked it will rarefy the air in the tube S O, on the principle and in the manner explained in (148.). The pressure of the air in S O on the surface

of the water within it being thus diminished, and rendered less than the pressure of the atmosphere on the exterior surface of the water in the well, a column of water will be forced in the tube S O by the excess of the atmospheric pressure. In proportion as the rarefaction of the air between the surface of the column suspended in the tube S O and the valve *x* is increased, in the same proportion will its pressure on the surface of the column be diminished, and so long as this diminution is continued the height of the column will increase. There is, however, a limit to this height. If the air could be altogether withdrawn from the tube S O, and an absolute vacuum produced beneath the valve *x*, like that which exists above the mercury in the barometer, then the atmospheric pressure, acting with undiminished effect on the surface of the water in the well, would sustain a column of water in the tube S O, the weight of which would be equal to a column of mercury with the same base, and having the height of the mercury in the barometer. Now the specific gravity of water is about 13½ times less than that of mercury, and consequently a force which could sustain a column of 30 inches of mercury would support a column of water 13½ times greater in height. If the barometer, therefore, be considered to stand at 30 inches, the atmospheric pressure would support a column of water of about 405 inches or 34 feet. From this consideration it will appear that if the operation of the syringe were perfect, and that an absolute vacuum could be produced below the valve *x*, still the water could never ascend through that valve by the atmospheric pressure, if its height above the level of the water in the cistern exceeded 13½ times the height of the barometric column. In these countries the barometric column varies between 28 and 31 inches in height, and therefore the valve *x* ought not to be more than 30 feet above the level of the water in the well. But it is still to be observed, that the construction and operation of the great syringe B C is subject to inevitable imperfections, which are always greater the larger the scale on which

the instrument is made. Even in small syringes accurately constructed a degree of imperfection exists, which has been already noticed in the explanation of the exhausting syringe; but such defects are greatly increased in a larger syringe, such as that used in common water pumps, where a common and less expensive mode of construction must be used.

From these causes, a column of water, which can be

Fig. 37.



raised in the tube S O, will be less than even 30 feet in height. It is obvious, however, that within this limit the length of the tube S O must be determined by the degree of excellence attained in the construction of the syringe C B.

When the rarefaction has been carried to a sufficient

extent, the tube S O being adjusted to a proper length, the column of water will rise until part of it pass through the valve *x*, and it will ascend to a level in the syringe B C, the height of which above the water in the well will be determined by the excess of the atmospheric pressure above the pressure which continues to act on the surface of the water in C B. The water which is thus drawn into the syringe presses by its weight on the valve *x*, and cannot return into the suction tube. When the piston is now pressed down, it will act on the water which has been raised above the valve *x* in the manner of the lifting pump already described, and the remainder of the process in raising the water will be in all respects the same as that which has been explained in reference to the lifting pump. In this case the water raised through the suction pipe, and deposited above the valve *x* in the syringe, serves as a well to the syringe, considered as a lifting pump. It is evident that, according as the water is elevated above the piston, the atmospheric pressure acting on the surface of the water in the well will force more water through the valve *x*. In this way the process is continued; during every ascent of the piston water being raised through the valve *x*, and during each descent of the piston the same quantity of water passing through the valve *v*. As the water accumulates above the piston, as described in the lifting pump, it at length reaches the spout from which it is discharged.

Such is the construction and operation of the common household pump. It may appear, at first view, that the pressure of the atmosphere sustaining the column of water in the suction tube furnishes an aid to the power which works the pump. This, however, is not the case; at least not so in the sense in which it is commonly understood. To make this intelligible, it will be necessary to consider somewhat in detail the forces which are in operation during the process. There are some forces which are directed downwards from the top of the syringe towards the bottom of the well, and others which

are directed upwards. Now it is evident that the mechanical power applied to draw the piston up will have to overcome all that excess by which the forces downwards exceed the forces upwards. Let us suppose a column of water resting on the piston, after having passed through the valve *v*. The upper surface of this column is pressed upon by the weight of the atmosphere; the piston has, therefore, this weight to sustain. It has also to sustain the weight of the water which is above it. The atmospheric pressure acting also on the water in the well, is transmitted by the quality of liquids explained in Hydrostatics, Chap. II., to the bottom of the piston; but this effect is diminished by the weight of the column of water between the surface of the water in the well and the bottom of the piston, for the atmospheric pressure must, in the first place, sustain that column, and can only act upon the bottom of the piston in the upward direction with that amount of force by which it exceeds the weight of the column of water between the piston and the well. The effect, therefore, on the piston is the same as if it were pressed downwards by the weight of the column of water between the piston and the well, and at the same time pressed upwards by the atmospheric pressure. Thus the piston may, in fact, be regarded as being urged downwards by the following forces, — the atmospheric pressure, the weight of the water above the piston, and the weight of the water between the piston and the well; that is to say, in fact, by the atmospheric pressure, together with the weight of all the water which has been raised from the well. At the same time, it is pressed upwards by the atmospheric pressure transmitted from the surface of the water in the well. This upward pressure will neutralise or destroy the effect of the same atmospheric pressure acting downwards on the surface of the water above the piston, and the effective downward force will be the weight of all the water which is contained in the pump.

By this reasoning, it appears that the pump must be worked with as much force as is equal to the weight of

all the water which is in it at any time, and, therefore, that the atmospheric pressure affords no aid to the working power.

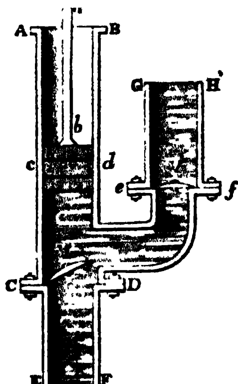
Since the action of the pump in raising water is subject to intermission, the stream discharged from the spout will necessarily flow by fits and irregularly, if some means be not adopted to prevent this. At the top of the pump a cistern may be constructed, with a view to remove this inconvenience. If the pump be worked, in the first instance, so as to raise more water in a given time than is discharged at the spout, the column of water will necessarily accumulate in the barrel of the pump above the spout. The cistern M N will, therefore, be filled, and this will continue until the elevation of the surface of the water in the cistern above the spout will produce such a pressure, that the velocity of discharge from the spout will be equal to the velocity with which the water is raised by the piston. The level of the water in the cistern will therefore cease to rise. This level, however, will be subject to a small variation as the piston rises; for while the piston is descending, the water is flowing from the spout, and no water is raised by the piston, consequently the level of the water in the cistern falls. When the piston rises, water is raised, and the quantity in the cistern is increased faster than it flows from the spout, consequently the level of the water in the cistern rises, and thus this level alternately rises and falls with the piston. But if the magnitude of the cistern be much greater than the section of the pump barrel, then this variation in the surface will be proportionally small, for the quantity of water which fills a part of the barrel, equal to the play of the piston, will produce a very slight change in the surface of the water in the cistern. The flow, therefore, from the spout S will be uniform, or nearly so.

The forcing Pump.

(168.) The forcing pump is an instrument which combines the principle of the suction and the lifting pump.

In *fig.* 38., C E, is a suction pipe which descends into the well, at the top of which is the suction valve V opening upwards. The pump barrel A B C D is furnished with a solid piston without a valve, and from the side of this barrel, just above the suction valve, there proceeds a pipe which communicates with an upright cylinder G H, which is carried to the height to which the water is intended to be raised. In the bottom of this cylinder is placed a valve V′, which opens upwards. In the commencement of the process the suction pipe

Fig. 38.



C E, and the chamber between the piston and valves, are filled with air. When the piston is depressed to the valve V, the air enclosed in the latter chamber becomes condensed, and, opening the valve V′, a part of it escapes. On raising the piston the air below it becomes rarefied, and the air in the suction pipe opening the valve V by its superior pressure, expands into the upper chamber: a part of it is expelled through the valve V′, when the piston next descends. During this process, it is evident that the pump acts as an air pump or exhausting syringe, and is in all respects equivalent to the instrument described in (148.). When the air

becomes sufficiently rarefied by this process, the atmospheric pressure forces water from the well through the suction pipe and the valve V into the chamber between the piston and the valves. When the piston now descends, it presses on the surface of the water, and the valve V opening upwards prevents the return of the water into the suction pipe; while the pressure of the piston, being transmitted by the water to the valve V', opens it, and, as the piston descends, the water passes into the force pipe G H. The next ascent of the piston allows more water to pass through the valve V, and the next descent forces this water through the valve V' into the force pipe. By continuing this process, the quantity of water in the force pipe continually increases, receiving equal additions at each descent of the piston.

It is evident that the force pipe may be placed in any position, whether perpendicularly, obliquely, or horizontally, and that, in every case, the action of the piston will propel the water through it.

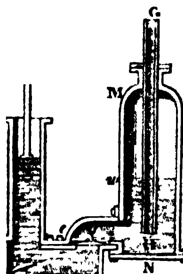
When the piston is pressed downwards, and the valve V' is opened, it is necessary that the force which works the piston should balance the weight of the column of water in the force pipe, for this weight is transmitted by the water between the piston and force pipe to the bottom of the piston; consequently, the height of the column of water in the force pipe will measure the intensity of the pressure against the base of the piston when the valve V' is open. A column of water about 34 feet in height, suspended in the force pipe, will press on the base of the piston with a force of about 15 pounds on each square inch, and the pressure at other heights will be proportional to this. The force necessary to urge the piston downwards may, therefore, always be calculated. In drawing the piston up the valve V' is closed, and relieves the piston from the weight of the incumbent column; if the valve V is opened, the piston is subject to the same pressure as in the suction pump. This pressure has been already proved to be

equal to the weight of the column of water raised above the level of the water in the well.

It follows from this, that if the height of the force pipe be equal to the length of the suction pipe, then the piston must be pressed upwards and downwards with the same force; but if the height of the force pipe be greater or less than the length of the suction pipe, then the downward pressure must be greater or less, in the same proportion, than the force which draws the piston up. In fact, the force which draws the piston up in this pump, after the water has been raised to the valve, is uniform, while the force with which the piston must be urged downwards is continually increasing, until the water in the force pipe reaches its point of discharge, and until the discharge becomes equal to the supply.

The supply of water by the force pipe through the valve V', is evidently intermitting, being suspended during the ascent of the piston; it follows, therefore, that the flow from the point of discharge will be liable to the same intermission, if means be not adapted to counteract this effect. A cistern placed at the top of

Fig. 39.



the force pipe, as already described in the suction pump, may serve the purpose, but it is generally more convenient to use an apparatus called an air vessel, which is represented in *fig.* 39. Immediately above the valve

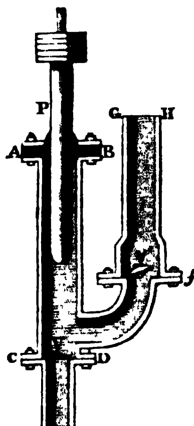
V′ a short tube communicates with a strong close vessel of sufficient capacity; through the top of this vessel the force pipe G H passes, and descends to a point near the bottom. By the action of the pump the water is forced into the vessel M N, and when its surface rises above the mouth H of the force pipe, the air in the vessel M N is confined above the water; and as the water is gradually forced in, this air is compressed, and acts with increased elastic force on the surface of the water: this pressure forces a column of water into the pipe H G, and maintains that column at an elevation proportional to the elastic force of the condensed air. When the air in the vessel M is reduced to half its original bulk, it will act on the surface of the water with double the atmospheric pressure; meanwhile, the water in the force pipe being subject only to once the atmospheric pressure, there is an unresisted upward force equal to the atmospheric pressure which sustains the column of water in the tube: a column will then be sustained about 34 feet in height. When the air is reduced to one third of its original bulk, the height of the column which it can sustain is 68 feet, and so on. If the force pipe terminate in a ball pierced with small holes, so as to form a *jet d'eau*, the elastic pressure of the air on the surface will cause the water to spout from the holes.

It is of great importance in the forcing pump that the piston should be truly water-tight in the cylinder, and in practice this is not always very easily accomplished. The arrangement represented in *fig.* 40. is better adapted to insure the perfect action of the pump than the form of piston already represented. In this case a polished cylindrical metal plunger P passes through a collar of leathers A B, which exactly fits it; and it is maintained perfectly air-tight and water-tight by being lubricated with oil or tallow. When the plunger is raised, the space it deserts is replaced by the water which rises through the valve V; and when it descends, the water which filled the space into which it

advances is driven before it through the valve V′ into the force pipe.

If the forcing pump, represented in *fig.* 38., be attentively considered, it will be perceived that the principles on which the piston acts in its ascent and descent are

Fig. 40.

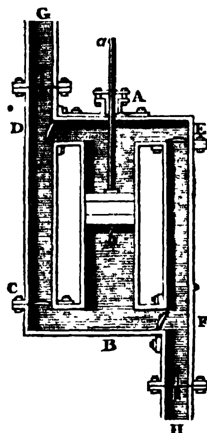


perfectly distinct. In its ascent it is employed in drawing the water from the suction pipe into the pump barrel, and in its descent it is employed in forcing that water from the pump barrel into the force pipe. Now the piston being solid, and not furnished with any valve, there is no reason why its upper surface should not be employed in raising or propelling water as well as the lower. While the lower surface is employed in drawing water from the suction pipe, the upper surface might be employed in propelling water into the force pipe; and, on the other hand, in the descent of the piston, when the lower surface is employed in propelling water into the force pipe, the upper surface might be engaged in drawing water from the suction pipe. To accomplish this, it is only necessary that the top of the cylinder

should be closed, and that the piston rod should play through an air-tight collar, the top of the cylinder communicating with the force pipe and the suction pipe, as well as the bottom.

Such an arrangement is represented in *fig.* 41. When the piston ascends, the suction valve F is opened, and water is drawn into the pump barrel below the piston; and when the piston descends, the suction valve F is

Fig. 41.



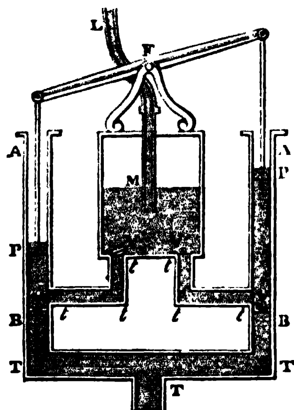
closed, and the pressure of the piston on the water below it opens the valve C, and propels the water into the force pipe C G. Also, while the piston is descending, water rises through the suction valve E into the barrel above the piston; and when the piston ascends, the water being pressed upwards keeps the valve E closed, and opens the valve D, and is thus propelled into the force pipe. By this arrangement the force pipe receives a continual supply of water from the pump barrel without any intermission; and in like manner the pump barrel receives an unremitting flow from the suction pipe. This will be distinctly seen, if it is considered

that either of the two suction valves E or F must be always open. If the piston descends, the valve E is open and F is closed; and if the piston ascends, the valve E is closed and the valve F is open: a stream, therefore, continually flows through the one valve or the other into the pump barrel. In like manner, whether the piston ascends or descends, one of the valves C or D must be open: if it descends, the valve D is closed and C is open; if it ascends, the valve D is open and C is closed.

The Fire Engine

(169.) The fire engine is subject to a variety of different forms, which all, however, agree in one principle. It generally consists of a double forcing pump communicating with the same air vessel, and instead of a force pipe a flexible leather hose is used, through which the water is driven by the pressure of the condensed air in the air vessel. A section of the apparatus is represented in *fig.* 42. T is a pipe which descends into the receiver,

Fig. 42.



or to any vessel containing the supply of water. This pipe communicates with two suction valves V, which open

into the pump barrels of two forcing pumps A B, in which solid pistons P are placed. The piston rods of these are connected with a working beam, so arranged that a number of different persons may act on both sides of it. Force pipes proceed from the sides of the pump barrel above the valves V, and they communicate with an air vessel M, by means of valves V, which also open upwards. The pipe descends into the air vessel near the bottom, as already described in *fig.* 39. This pipe is connected with the flexible leathern hose L, the length of which is adapted to the purposes to which the machine is to be applied. The extremity of the hose may be carried in any direction, and may be introduced through the doors or windows of buildings. By the alternate action of the pistons water is drawn through the suction valve, and propelled through the forcing valves V′, until the air in the top of the vessel M becomes highly compressed. This pressure acts continually on the surface of the water in the vessel, and forces it through the leathern hose, so as to spout from its extremity with a force depending partly on the degree of condensation, and partly on the elevation of the extremity of the hose above the level of the engine. It is to be considered that the pressure of the condensed air has, in the first instance, to support a column of water, the height of which is equal to the level of the end of the tube above the level of the water in the air vessel; and until the pressure of the condensed air exceeds what is necessary for this purpose no water can spout from the end of the hose; and, subsequently, the force with which it will so spout will be proportional to the excess of the pressure of the condensed air above the weight of the column of water, whose height is equal to the elevation of the end of the hose above the level of the water in the air vessel.

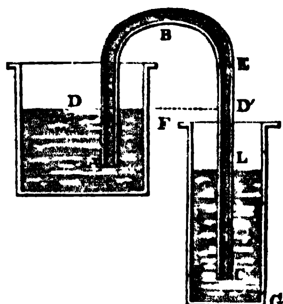
The Siphon.

(170.) The siphon is a contrivance by which a liquid may be conducted from one vessel to another

through an intermediate channel or pipe, which rises above the natural level of the water.

Let D, *fig.* 43., be a cistern containing a liquid, and

Fig. 43.



et B be the height over which it is necessary to conduct that liquid. Let A B C be a bent tube open at both ends, and let the leg B A be immersed in the liquid which it is required to transfer, and let the end C be directed into the vessel to which it is intended to remove it. Let the air which fills the tube D B C be drawn from it by the mouth applied at C, or by an exhausting syringe. The atmospheric pressure immediately taking effect on the surface D of the water in the cistern will press the water into the tube A B, towards the point B; and if the point B be not at a greater height above the level of the cistern than 32 feet, then the water will rise to the highest point B, and will flow so as to fill the entire tube to the mouth C.

To comprehend the principle upon which the siphon acts, let us suppose the water at the point B acted upon by two pressures, one towards C, and the other towards D. It will move in the one direction or in the other according as the one or the other pressure prevails. The atmospheric pressure acting on the surface D supports the column in the siphon between the surface and

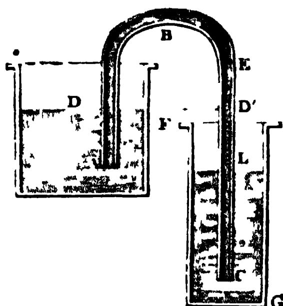
the point B, and it presses the water at B towards C with a pressure equal to the amount by which the atmospheric pressure exceeds the weight of the column D B, which it sustains in the siphon. The atmospheric pressure also acts at the mouth C of the siphon, and is resisted by the weight of the column C B. It exerts a pressure on the water at B, amounting to the excess of the atmospheric pressure above the weight of the column C B. Thus it appears that the water at B is urged towards C by a force equal to that pressure by which the atmospheric pressure exceeds the weight of the water in B D, and this force is resisted by a force equal to that by which the same atmospheric pressure exceeds the weight of the water in C B. Now, since the atmospheric pressure exceeds the weight of the water in D B by a greater quantity than it exceeds the weight of the water in B C, it follows that B will be urged towards C with a greater force than it is urged towards D, and, therefore, that it will move towards C. It is evident that the excess of the force which urges it towards C above the force which urges it towards D will be equal to the weight of the column of water C which is contained in the longer leg of the siphon below the level of the water in the cistern D.

If the leg of the siphon terminate at D′, the forces which would act on the water at B would be equal, for the one would be the atmospheric pressure diminished by the weight of the water in B D, and the other would be the atmospheric pressure diminished by the weight of the water in B D′; but the weight of the water in B D and B D′ being equal, the forces which act on the water at B will also be equal, therefore no water will flow from the siphon. If the leg of the siphon terminate above D′ as at E, then the pressure on the water at B, the siphon being supposed to be filled, will be greater in the direction at B D than in the direction at B C, and, therefore, the water will flow back into the cistern, and the siphon will be useless.

Let F G be a vessel to which the liquid is to be transferred. When it rises in this vessel above the mouth

C to any higher level as L, then the weight of the water in the leg below L will be balanced by the pressure of the water in the vessel F G, and, therefore, the efficient leg of the siphon will be B L. Thus, as the surface of

Fig. 43.



the water rises in the vessel F G, the actual leg of the siphon is shortened. When the surface L has risen towards the level of the surface D, then the legs of the siphon become equal, and, by what has been already stated, its action must cease.

It thus appears that the siphon is merely an instrument used in decanting a liquid, but that it does not perform the office of a pump in raising it above the level which it held in the vessel from which it is drawn.

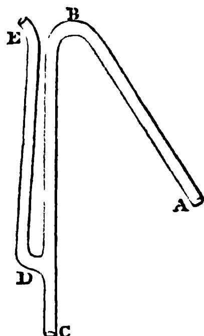
The process of exhausting the syringe by suction, or otherwise, is frequently difficult and always inconvenient. But this may be avoided by presenting the legs of the siphon upwards in the first instance, and having stopped the shorter leg with the hand, filling the siphon through the longer leg C B. Both ends of the tube being then stopped, let them be pressed downwards, the shorter leg being introduced below the water in the cistern, and the longer leg being carried over the vessel in which the liquid is to be decanted.

The process of exhaustion is sometimes facilitated in

the following manner: — A small tube proceeds from the longer leg near its extremity at D, *fig.* 44. The extremity A being immersed in the liquid, and the extremity C being stopped by the hand, the mouth applied at the extremity E of the subsidiary tube will exhaust the siphon and cause the water to rise in it.

When the siphon is constructed upon a very large

Fig. 44.

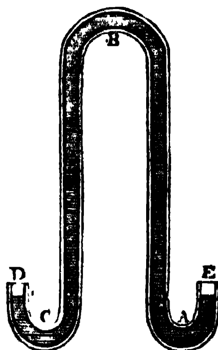


scale this process is impracticable. In that case both ends of the tube A and C may be first plugged, and a hole being made at the highest part B, the instrument may be filled with liquid. The hole through which it is filled being then plugged, and the extremities opened, the instrument will act. A siphon of any magnitude may thus be constructed, and water may be carried over a hill, the perpendicular height of the top of the siphon not exceeding 34 feet above the level of the reservoir from which the water is to be drawn; but it is obvious, also, that the basin into which it is discharged must not be higher than the level of the receiver from which it is drawn.

The Wurtemburg siphon has the convenience, when once filled of always remaining so, the waste by evaporation only being supplied. This instrument is represented in *fig.* 45. When not in use it may be hung up

upon a hook or nail by the curved part B. The ends D and E will then be presented upwards, the liquid being retained in the siphon by the atmospheric pressure acting on both surfaces at D and E. When the leg B C D is immersed in a vessel of liquid, the surface D is pressed down by the weight of the incumbent liquid, and also by the atmospheric pressure acting above that. This pressure is transmitted to E, where it is resisted by the atmospheric pressure only, consequently the

Fig. 45.



water will be driven from E with a force equivalent to the hydrostatic pressure on the surface D.

CHAP. VII.

THE AIR GUN, AIR BALLOON, AND DIVING BELL.

THE AIR GUN. — FIRST ATTEMPTS AT BALLOONS. — LANA'S BALLOON OF RAREFIED AIR. — FIRE BALLOONS. — MONTGOLFIER'S BALLOON — FIRST ASCENT. — BALLOONS INFLATED WITH HYDROGEN. — PARACHUTE. — BLANCHARD'S EXPERIMENT. — CAUSES OF THE EFFICACY OF THE PARACHUTE. — ASCENT OF GAY LUSSAC AND BIOT. — APPEARANCES IN THE HIGHER REGIONS OF THE ATMOSPHERE. — THE DIVING BELL.

The Air Gun.

(171.) THE air gun is an instrument for projecting balls or other missiles by the elastic force of condensed air.

A strong metal ball is constructed, furnished with a small hole, and a valve opening inwards: in this ball air may be condensed to any degree which its strength is capable of bearing, by means of a condensing syringe screwed into the hole.

When this condensation has been accomplished, the ball is detached from the syringe and screwed at the breech of a gun, constructed so that a trigger is capable of opening the valve. The ball being placed in the barrel near the breech, and fitting the barrel so as to be air-tight, is exposed to the pressure of the condensed air the moment the valve is opened: this pressure propels it along the barrel, and continues to act upon it so long as the valve is opened. It is thus projected from the gun in the same manner as that in which a ball is urged by the expansive force of exploded gunpowder. The force of projection obviously depends on the degree of condensation which is given to the air in the ball.

The stock of the gun may contain a magazine of balls, and be furnished with a simple mechanism by which these balls may be transferred in succession into the barrel, so that the gun is easily and quickly loaded after each discharge.

The magazine of condensed air may receive different shapes and be differently arranged, but that which is now described is one of the best forms for it.

The Air Balloon.

(172.) The physical conditions under which a solid body immersed in a liquid will rise to the surface, sink to the bottom, or remain suspended, have been fully detailed in a former part of this volume. (Hydrostatics, Chapter V.)

If a body be heavier than the quantity of liquid, the place of which it occupies, it will sink by that preponderance. If it be equal in weight to the liquid it displaces, it will remain suspended, as the liquid itself would; but, if it be lighter than the liquid which is displaced, the superior weight of the surrounding liquid will press it upwards, and will cause it to ascend to the surface.

Liquids being incompressible, all their strata have the same density, or nearly so; and, consequently, a solid which at one depth is lighter than the liquid which it displaces, will also be lighter at every depth. Consequently, if a solid has a tendency to rise towards the surface at any depth, it will continue so to rise until it reach the surface. If, however, the strata of liquid approaching the surface had gradually decreased in density, then the solid, which was lighter, bulk for bulk, than an inferior stratum, might be equal in weight, bulk for bulk, to a superior one, and heavier, bulk for bulk, than others nearer to the surface. Thus, such a body would rise at certain depths, but at other lesser depths it would sink; and at the depth of a certain stratum it would remain suspended.

The property of liquids, which is the cause of these phenomena, is their power of freely transmitting pressure. This will be plainly perceived by referring to (55.), where it is shown that the solid rises to the surface by the pressure of the column of the liquid whose base is contiguous to it, and rests on the same level, and

which pressure is transferred to the base of the solid by the inferior strata of liquid. Now this property of transmitting pressure is common to elastic fluids, and we are, therefore, warranted in the inference, that a solid suspended in a gaseous fluid, which is lighter, bulk for bulk, than the fluid, will rise; that if it be heavier, bulk for bulk, it will fall; and if it be equal in weight, bulk for bulk, it will remain suspended. That a solid, therefore, may rise in the atmosphere with any given force, it is only necessary that its weight should be less than the weight of the air which it displaces by the amount of that force. Upon this principle BALLOONS are constructed.

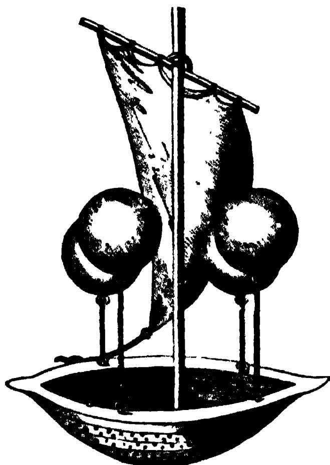
The method of constructing a balloon, which naturally first suggests itself, is to exhaust a large chamber of the air which it contains, so as to render it a vacuum, or nearly so: it will then continue to displace the same quantity of atmosphere as before, but its weight will be diminished by the weight of the air withdrawn from the chamber, and it will have a disposition to rise in the atmosphere proportionate to the difference between the actual weight of the materials which form the chamber and the weight of the air whose place it occupies. This was, accordingly, the method adopted in the earliest attempts on record to construct balloons. About the middle of the seventeenth century, a Jesuit named Francis Lana constructed four hollow spheres of copper, each twenty feet in diameter, and so thin that the total weight of the copper composing them was less than the weight of the air which they would displace.

He proposed to attach these spheres to a boat furnished with a sail, as represented in *fig.* 46., by which means he hoped to traverse the clouds.

The method of exhaustion which Lana possessed was insufficient to accomplish his purpose; but even had it been otherwise, the atmospheric pressure acting on the external surface of the attenuated metal globes would have crushed them, and proved the project to be impracticable. It may be stated generally, that no known

solid possesses sufficient strength to enable a globe, or any other vessel formed of it, to resist the atmospheric pressure from without, when that pressure is not balanced by a corresponding pressure from within, unless

Fig. 46.

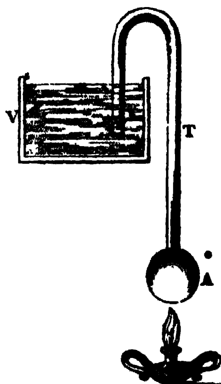


it be made of so great a thickness that its weight will very much exceed the weight of the air which it displaces.

To give sufficient buoyancy to a large hollow body, and at the same time to secure it from the effect of atmospheric pressure, it will be therefore necessary to fill it with some elastic fluid, which will, by its elasticity, balance the effect of the external air, and, by its small specific weight, produce a degree of buoyancy sufficient to raise the materials of which it is constructed. In this case, as the forces which act on the balloon are held in a state of equilibrium, or nearly so, no extraordinary degree of strength is required, and any extremely light and flexible substance impervious to air or gas may be used.

The most obvious contrivance which is suggested by these considerations is atmospheric air rarefied by heat; for in this case, the expansion produced by the heat gives the same degree of elasticity with a much less quantity of atmospheric air. To explain this, let a glass bulb A be furnished with a tube T, which, rising from it to the extremity at which it is curved, descends into a vessel V, *fig.* 47., containing water or other liquid: the air is thus enclosed in the tube in the common state of the external atmosphere. Let a spirit lamp, or any other source of heat, be now applied to the bulb at A;

Fig. 47.



the air in the bulb receiving increased elasticity from the heat will press the water towards the mouth of the tube, and, rising in bubbles, will escape at the surface of the water. This will continue until the air in the tube is highly rarefied; still, however, retaining a degree of elasticity sufficient to balance the atmospheric pressure acting on the surface of the water in the vessel, and transmitted by it to the surface of the water in the tube. That the air in the tube is highly rarefied, may be verified by removing the lamp from the bulb: as the tube cools, the air will contract itself into its former dimensions, and the pressure of the atmosphere will

force the liquid through the mouth of the tube and over the curved part into the bulb. It will be found, that in this way the bulb and tube will be filled, with the exception of a very small bubble of air, which will remain suspended at the highest point of the tube: this bubble will have the same temperature as the external air, and the same pressure; and it is obvious, that this is as much lighter than the air which originally filled the tube and bulb, as its present magnitude is less than the whole contents of the bulb and tube.

If instead of a glass bulb we take a large spherical bag constructed of any light substance, and having in one part a circular opening or hole, this bag may be distended by blowing into it common air. If the hole be then presented downwards, and a lamp suspended beneath it, the flame of the lamp will gradually increase the temperature of the air contained in the bag: it will thus acquire increased elastic force, by which a part will be expelled at the hole under which the lamp is suspended. This process of rarefaction will be continued so long as the air contained in the bag receives increased temperature from the heat of the lamp; but throughout the whole process the elastic force of the rarefied air will be equal to the external pressure of the atmosphere, and the bag will be subject to no force tending either to burst it or to crush it.

Such a bag, if constructed of sufficient magnitude, may by these means be rendered lighter than the air which it displaces. It will thus have a corresponding buoyancy, and will ascend in the atmosphere with a force equal to the difference between its own weight and the weight of the air which it displaces.

The application of these principles form the first successful attempt in aeronautics. In the year 1782, two paper-makers, named Montgolfier, residing at Annonai, in France, constructed a bag of silk, in the form of a square box, containing about 40 solid feet when filled. In the bottom of this was placed an aperture, under which burning paper was applied: it ascended to nearly 100 feet in the air. The experiment was immediately

instituted on a larger scale. A balloon, constructed of a capacity exceeding 700 solid feet, rose in the same manner to an elevation of more than 600 feet. A balloon of the spherical form, but on a scale still larger, was next constructed: it contained 23,000 feet, and had a buoyancy capable of raising 500 pounds. It ascended in the atmosphere to a height of about 6000 feet.

Hitherto the experiments were confined to the object of ascertaining the mere possibility of ascending in the atmosphere; and, in some cases, the effects produced on animal life at great elevations were tried, by sending up various animals contained in a basket of wicker-work suspended from the balloon.

At length, in the latter end of the year 1783, a balloon was constructed at Paris, with a view to transport one or more persons into the higher regions of the atmosphere. This machine was composed of an elliptical bag, 74 feet in height and 48 in diameter. Immediately under an aperture in the bottom of the bag was suspended an iron grate within reach of the aeronaut, on which was placed the burning fuel to maintain the rarefaction within the balloon. An ascent was made to a height of about 3000 feet by M. Pilatre de Roziere and the marquis d'Arlandes. After this experiment various others succeeded in balloons constructed in the same manner.

The first projector of these balloons conceived that the machine owed its buoyancy to the gas produced by the fire, and which with an elastic pressure equal to the air was specifically lighter; still the mechanical principle of the ascent was not mistaken.

The step from fire balloons to balloons filled with gas specifically lighter than atmospheric air, of the same pressure, was now easy and obvious. The gas at present denominated hydrogen was submitted to a series of experiments, by which it was found that its specific gravity was only one seventh of that of common atmospheric air. It was obvious, therefore, that a balloon filled with this gas would have considerable buoyancy. Balloons were accordingly constructed and inflated with this gas, and

various ascents have since been made, the particulars of which would not be suitable to the limits of the present treatise.

The density of each stratum of air being proportional to the pressure under which it is placed, it follows that in ascending in the atmosphere the strata will have less and less specific gravity. A balloon, therefore, containing gas which balances the lower strata, will, if it be completely filled, have a tendency to burst when it has ascended into the higher strata; for the gas, not having room to expand, will maintain its original elastic force, while the atmospheric pressure being diminished in the ascent will cease to balance this elastic force of the confined gas. There will then be a bursting pressure equivalent to the excess of the atmospheric pressure of the lower strata over the atmospheric pressure in the strata to which the balloon has ascended.

These effects may be provided against by imperfectly filling the balloon in the first instance, so that as it ascends, the gas which it contains will have room to expand, and thus, while the pressure of the atmosphere is diminished, the elastic pressure of the gas in the balloon will be diminished in the same proportion. So long as the atmospheric pressure is not diminished to that degree which would cause the gas enclosed in the balloon to expand, so as to completely inflate it, no force tending to burst the balloon can exist; but should the ascent be continued to a greater height, then a bursting pressure will be called into action by the pressure of the atmosphere being diminished in a greater degree than the elastic force of the gas in the balloon. In this case the danger may be removed by the provision of a valve opening in some convenient part of the balloon, by which a part of the gas may be allowed to escape. Such a valve is also necessary in order to enable the aeronaut to descend at pleasure. Without it he would be compelled to remain in the atmosphere as long as the balloon continued to retain the gas with which it was inflated; but provided with such a valve, he can allow any portion of the gas to escape, and thereby diminish the magnitude of the bal-

loon, and consequently produce a corresponding decrease in its buoyancy.

By analogy, we should infer that the power of ascending at pleasure would be obtained by being able to supply an increased quantity of gas to the balloon; but this would not be easily practicable; and, accordingly, the power of ascending has been obtained by carrying up sand-bags, or other weights called ballast, by throwing out which the machine is lightened, and caused to ascend; or if from any accidental cause it should be found to fall with dangerous precipitancy, its rate of descent may be retarded by throwing out this ballast.

The principal cause of danger attending aeronautical experiments arises from the accidental escape of the gas from the balloon; and it has consequently been a desirable object to contrive means, in such cases, for rendering the fall of the aeronaut less liable to dangerous effects. With this view, an apparatus has been contrived, called a *parachute*. It is usually formed like a large umbrella, which spreads above the car with its concave side presented downwards. The effect of this acting against the air below is, to break the descent, and after a short time the rate of descent becomes uniform, instead of being, as heavy bodies generally are, accelerated. The magnitude of the parachute may be such, that the rate of descent shall be so slow that no danger is to be apprehended from the concussion attending the fall. If, therefore, the aeronaut descend on land, his safety is insured.

The subjects of the first experiments with the parachute were naturally inferior animals. M. Blanchard dropped a dog suspended from a parachute, from the altitude of 6000 feet above the surface of the earth. A whirlwind interrupted its descent, and carried it above the clouds. The aeronaut soon after met the parachute again; the dog recognised its master, and expressed his uneasiness and solicitude by barking; another current of air, however, carried him off, and he was lost sight of. The parachute with the dog descended soon after the

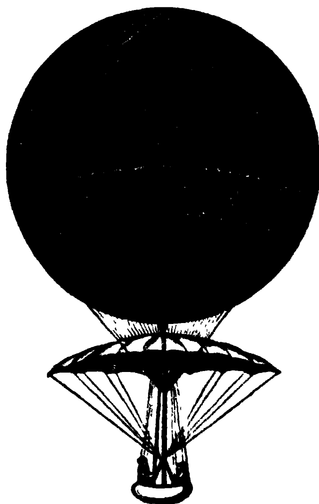
aeronaut in safety. Ten years after this, M. Garnerin made several successful experiments with the parachute. He placed it half expanded between the balloon and the car, so as to spread like an umbrella above him. At the height of about 2000 feet he had the intrepidity to cut off the parachute and car from the balloon. He descended slowly, the parachute gradually unfolding itself, and finally reached the ground in safety. The same experiment was several times repeated with similar success. In one case he descended from the perpendicular height of 8000 feet.

As the balloon derives its efficacy from the weight of the atmosphere, the parachute depends on the inertia of that fluid. In descending, the broad concave surface of the parachute must drive before it the column of air extending from its surface to the ground; but the circumstance on which its principal excellence depends is, that the resistance arising from this inertia increases in a more rapid proportion than the velocity of descent. A double velocity in the parachute would produce a fourfold resistance in the air; a threefold velocity would produce a ninefold resistance; a fourfold velocity a sixteenfold resistance, and so on. The law of this resistance has been already fully explained respecting liquids in (107.); and it may be explained in the case of the atmosphere in exactly the same words; but in the case of the descent of the parachute from great elevations, there is an obvious cause which makes the resistance increase even in a more rapid proportion than is indicated by this law. The increase of the resistance in the proportion of the square of the velocity arises from the supposition that the resisting fluid through which the body moves continues to be of the same density. Now this is not the case with the atmospheric air through which the parachute falls; each stratum into which it enters has a density greater than that from which it descends, and consequently on that account alone will offer a proportionally increased resistance. This cause, added to the former, will very speedily compel the para-

chute to descend with a uniform velocity. This velocity will be small in the same proportion as the parachute is large, and as the weight of the car and its contents is small.

As the gas by which a balloon is inflated is lighter than the atmosphere, the valve provided for its escape, when the aeronaut wishes to descend, is placed usually in the top of the balloon. If it were placed in the bottom, even although it were open, the gas would not escape; at least not in any considerable quantity, nor with any degree of certainty. The superior pressure of the atmosphere, and the natural levity of the gas itself, would prevent its escape; but when the valve is placed in the top, the gas will issue from it on the same principle as a lighter fluid rises in a heavier. The car which bears the aeronaut is usually

Fig. 48.



supported by a net-work which extends over the balloon,

and which is connected with it by a number of ropes and strings, as represented in *fig*. 48.

The total impracticability of guiding or governing balloons in their course through the air, has hitherto prevented them from being applied to any purpose of extensive utility. Scientific men have, on some occasions, ascended in the atmosphere, with a view of observing at great elevations the effect of temperature, pressure, electricity, and other phenomena connected with meteorology. In 1804, M. Gay Lussac and M. Biot made an ascent from Paris, furnished with various meteorological apparatus, to a height of upwards of 13,000 feet. Soon afterwards, M. Gay Lussac ascended alone, to a height of 23,000 feet above Paris. In 1807, M. Garnerin ascended at ten o'clock at night from Paris, and, rising with unusual rapidity, soon attained an immense elevation above the clouds. By some neglect, the apparatus for discharging the gas from the balloon was found to be unmanageable, and the high degree of rarefaction at so great an elevation produced in the balloon such a tendency to burst, that the aeronaut was obliged to cut a hole in the silk to allow the escape of the air. The balloon then descended with such rapidity, that he was obliged to counteract its motion by casting out all his ballast. The balloon thus continued alternately rising and sinking for nearly eight hours, during which he experienced the effects of a thunder storm, by which he was finally dashed against the mountains. He landed at Mont Tonnere, at a distance of 300 miles from Paris.

The effects produced on the aeronaut by the rarefaction of the atmosphere at great elevations, are sensibly manifested in respiration; the pulse is rendered more rapid, the head unusually swelled, and the throat parched.

The intense cold which also necessarily accompanies rarefaction produces great inconveniences, and an irresistible disposition to sleep is felt.

It has been found also that storms and currents in the atmosphere are local, and that while one stratum is thus

agitated, other strata inferior or superior to it will be calm. By managing his ascent or descent, the aeronaut may thus transfer himself from wind to stillness, from a storm to a calm, or from one current of wind to another in a different direction. The velocity with which balloons are sometimes transported through the air amounts to eighty miles an hour. The appearance of the clouds from great heights is said to resemble a plain of snow, or a sea of white cotton. Those which are charged with electricity are said to resemble the smoke of ordnance. Clouds containing hail or snow are often encountered, in which the car becomes almost filled with these substances. Clouds of mist or rain frequently drench the aeronaut. When birds are allowed to escape from the balloon at a great height, they fall almost perpendicularly downwards, the attenuated air not having sufficient inertia to offer resistance to their wings.*

Attempts have been made to render balloons useful in military operations, by viewing from an elevated position the disposition and movements of an hostile army. An academy, with this object, was actually established at Neudon, near Paris, during the late war, where a corps of aeronauts was trained to the service. A balloon was kept constantly inflated, and secured to the ground by a rope, which allowed it to ascend to a height of about twenty-five yards. At this institution military balloons were prepared for the different divisions of the French army; and on one occasion an ascent was made by a French general, at the battle of Fleury, to a height of nearly 500 yards, from which he reconnoitred the hostile armies. It is said that the signals which were made to general Jourdan on this occasion decided the fate of the engagement. The project, however, has long since been abandoned, not being found generally available.

It has been proposed to render balloons useful in geographical surveys, both as a means of raising the observer to great elevations, and of transmitting signals to great distances.

* The Edinburgh Encyclopædia, article Aeronautics.

The Diving Bell.

(173.) The spirit of enquiry which so strongly characterises the human mind, and which stimulates man to undertakings in which life itself is imminently risked, has not only prompted him to ascend into the regions of the air, but has also carried him to the depths of the sea.

The practice of diving is of very early origin, and was first probably adopted for the recovery of articles of value dropped into the water at small depths. Instances are recorded of persons having acquired by practice the habit of enduring submersion for a length of time, which in many cases seems astonishing, and in others altogether incredible. Indeed, the circumstances attending most of these narrations bear unequivocal marks of fiction. The gratification of a taste for the marvellous does not tempt us to allow a space in our pages for a description of the feats of the Sicilian diver, whose chest was so capacious that by one inspiration he could draw in sufficient air to last him a whole day, during which time he would sojourn at the bottom of the sea, and who became so inured to the water, that it was almost a matter of indifference to him whether he walked on dry land or swam in the deep, remaining often for five days in the sea, living upon the fish which he caught!

Various attempts were made to assist the diver by enabling him to carry down a supply of air; and after a long period and gradual improvements, suggested by experience, the present diving-bell was produced.

This machine depends for its efficacy on that quality in air which is common to all material substances, impenetrability; that is, the total exclusion of all other bodies from the space in which it is present. The diving-bell is a large vessel closed at the sides and at the top, but open at the bottom. It should be perfectly impenetrable to air and water. When such a machine, with its mouth downwards, is pressed into the water by sufficient weights suspended from it, the air contained in it at the surface will be enclosed by the sides, the top, and the surface of

the water which enters the mouth of the machine. As it descends in the liquid, the air inclosed in it is subject to the pressure which increases in proportion to the depth, and by virtue of its elasticity will become condensed in proportion to this pressure. Thus at the depth of about 34 feet, the hydrostatic pressure will be equal to that of the atmosphere; and since the air at the surface of the water is under the atmospheric pressure, it will be affected by double the pressure at the depth of 34 feet. It will, therefore, conformably to what was explained in (132.) be condensed so much as to be reduced to half its original dimensions. Half the capacity of the machine will, therefore, be filled with water, and the other half will contain all the air which filled the machine at the moment of its immersion. As the depth is increased, the space occupied by the air in the bell will be proportionably diminished.

It is well known that if an animal continue to respire in a space from which a fresh supply of atmospheric air is excluded, the air confined in the space will at length become unfit for the support of life. This is owing to an effect produced upon the air drawn into the lungs, by which when breathed it contains carbonic acid, an ingredient not present in the natural atmosphere, and which is highly destructive to animal life. When the air in which the animal is confined has been breathed for a length of time, this effect being repeated, the air enclosed becomes highly impregnated with this gas; and if its escape be not allowed, and a fresh supply of atmospheric air admitted, the animal cannot live. If, therefore, a diving-bell be used to enable persons to descend in water, it will be necessary either to raise them to the surface after that interval in which the air confined in the bell becomes unfit for respiration, or means must be adopted to send down a supply of fresh air, and to allow the impure air to escape. But besides this, there is another reason why means of sending down a supply of air are necessary. It has been already proved, that the hydrostatic pressure causes the water to fill a large part of the

capacity of the machine, the air contained in it being condensed. It is necessary, therefore, in order to maintain sufficient room for the diver free from water, to supply such a quantity of air, as that in its condensed state it will keep the surface of the water near the mouth of the machine. Thus, at the depth of 34 feet, it will be necessary to supply as much air as would fill the bell in its natural state. At double that depth, as much more will be necessary, and so on.

The air necessary for these purposes is supplied by one or more large condensing syringes, constructed on the principle explained in (162.). These syringes or pumps are placed above the surface of the water into which the bell is let down, and they communicate with the interior of the bell by a flexible tube carried through the water and under the mouth of the bell. Through this tube any quantity of fresh air, which may be requisite for either of the purposes already mentioned, may be supplied. A tube furnished with a stopcock is placed in the top of the bell, by which the diver can let any quantity of impure air escape to make room for the fresh air which is admitted. The impure air will rise by its levity in bubbles to the surface.

The diving bell received its name from the shape originally given to it. It was constructed with a round top, increasing in magnitude towards the mouth, thus resembling the shape of a bell. It is now, however, usually constructed square at the top and bottom, the bottom being a little larger than the top, and the sides slightly diverging from above. The material is sometimes cast iron, the whole machine being cast in one piece, and made very thick, so that there is no danger either from leakage or fracture. In this case the weight of the machine itself is sufficient to sink it. Diving bells, however, are also sometimes constructed of close grained wood, two planks being connected together with sheet lead between them.

In the top of the machine are placed several strong

glass lenses for the admission of light, such as are used in the decks of vessels to illuminate the apartments below.

The shape of the machine is generally oblong, with seats for the diver at the end, shelves for tools, writing materials, or any other articles necessary to be carried down, are placed at the sides; and below the seats there are boards placed across the machine to support the feet. Messages are communicated from below to above either in writing or by signals. A board is carried in the bell on which a written message may be chalked. This board communicates by a cord with the arm of the superintendent above, who, on a signal given, draws it up, and who, in a similar way, is able to return an answer.

When the bell is of cast iron, a system of signals may be made by very simple means: a blow struck by a hammer on the bell produces a peculiar sound distinctly audible at the surface of the water, and which cannot be mistaken for any other noise. The number of strokes made on the bell indicate the nature of the message, the smaller number of strokes signifying those messages most frequently necessary. Thus, a single stroke calls for a supply of fresh air; two strokes command the bell to stand still; three express a desire to be drawn up; four to be lowered, and higher numbers express motion in different directions. Of course this system of signals is arbitrary, and liable to be varied in different places.

The bell is usually suspended from a crane, which is placed above the surface of the water, and in order to move it this crane is placed on a railway, by which it is enabled to traverse a certain space in one direction. The carriage which traverses this railway supports another railway in directions at right angles to it, on which the crane is supported. By these means two motions may be given to the crane, the extent of which may be determined by the length of the railway, and the bell may be brought to any part of the bottom which is perpendicularly below the parallelogram formed by the length of the railway.

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THE END.

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